Wetlands: Ecology, Conservation and Management 7

Alexandros Stefanakis *Editor*

Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates

Springer

Wetlands: Ecology, Conservation and Management

Volume 7

The recognition that wetlands provide many values for people and are important foci for conservation worldwide has led to an increasing amount of research and management activity. This has resulted in an increased demand for high quality publications that outline both the value of wetlands and the many management steps necessary to ensure that they are maintained and even restored. Recent research and management activities in support of conservation and sustainable development provide a strong basis for the book series. The series presents current analyses of the many problems afflicting wetlands as well as assessments of their conservation status. Current research is described by leading academics and scientists from the biological and social sciences. Leading practitioners and managers provide analyses based on their vast experience.

The series provides an avenue for describing and explaining the functioning and processes that support the many wonderful and valuable wetland habitats, such as swamps, lagoons and marshes, and their species, such as waterbirds, plants and fish, as well as the most recent research directions. Proposals cover current research, conservation and management issues from around the world and provide the reader with new and relevant perspectives on wetland issues.

Alexandros Stefanakis
Editor

Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates

Springer

Editor
Alexandros Stefanakis
Laboratory of Environmental Engineering and Management,
School of Chemical and Environmental Engineering
Technical University of Crete
Chania, Greece

ISSN 1875-1261 ISSN 1875-127X (electronic)
Wetlands: Ecology, Conservation and Management
ISBN 978-3-031-03599-9 ISBN 978-3-031-03600-2 (eBook)
https://doi.org/10.1007/978-3-031-03600-2

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The idea for this book, and generally on the use and the potential of constructed wetlands in hot and arid climates, was born several years ago while working on wetland projects in countries with these climatic conditions. On the one hand, countries with this climate suffer from high to extreme water scarcity and limited freshwater resources, while the water demand is always increasing. On the other hand, wastewater in most of these countries is still viewed as a waste rather than as a valuable resource. Many factors contribute to this based on my experience, including financial and technical barriers as well as social and cultural aspects. But even if some of these barriers are lifted, circular management of treated effluents, for example, for reuse in irrigation, is typically not a priority. However, sustainable wastewater management is rapidly seen as an opportunity, and a shift is taking place slowly but steadily. Under these extreme climates, treated wastewater can be a significant new water source in the local and regional water balance. And this is where nature-based solutions such as constructed wetlands can play a critical role.

The technology of constructed wetlands is not new. While there are numerous applications in Central and Western Europe, North America, and Australia, it is much less frequently applied in regions with hot and arid climates (e.g., Middle East, Central and North Africa). We now know that this technology can be an ideal sustainable solution for wastewater management in these regions. From a technical point of view, the warmer climate and the higher temperatures favor many pollutant removal processes and further reduce the areal footprint. This technology also fits well the population patterns in these countries with many small, remote settlements where decentralized solutions are needed, as well as the economic and social characteristics that require cost-effective and easy-to-build and operate facilities.

The book you are holding is the first attempt to gather most of the available information and experience on constructed wetlands in hot and arid climates. The published literature on this topic is not extended and quite fragmented among journal papers and technical reports, considering also that this sustainable technology has not yet penetrated in deep the relevant markets. Therefore, the idea was to collect as many as possible of the existing case studies, research projects, and demonstration facilities that have been implemented in countries with this climate. The result proved to be more than satisfying. The book has 21 chapters with constructed wetlands examples and studies from 29 different countries, making it the first single reference in the international literature on this topic.

It is my hope that this book will successfully demonstrate to all relevant stakeholders the potential and benefits of this sustainable technology for the local/regional/national water sectors and contribute to the wider adoption and implementation of constructed wetlands for sustainable and circular wastewater management in these climatic regions.

Chania, Greece
10 April 2022

Alexandros Stefanakis

Contents

Contributors

Ghaida Abdallat Postdoctoral Researcher, University of Jordan, Amman, Jordan

Hussein I. Abdel-Shafy Water Research & Polluted Control Department, National Research Centre, Dokki, Cairo, Egypt

Muhammad Afzal Soil and Environmental Biotechnology Division, National Institute for Biotechnology and Genetic Engineering (NIBGE), Faisalabad, Pakistan

Wajihu Ahmada Fisheries Education and Training Agency, Mbegani Campus, Bagamoyo, Tanzania

Mushtaque Ahmed Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Oman

Tahra Talib Al-Rashdi Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Oman

Carlos A. Arias Department of Biology – Aquatic Biology, Aarhus University, Aarhus C, Denmark
WATEC Aarhus University Centre for Water Technology, Aarhus C, Denmark

Kirti Avishek Department of Civil and Environmental Engineering, Birla Institute of Technology, Ranchi, Jharkhand, India

Hassan Azaizeh Institute of Applied Research, Affiliated with the University of Haifa, The Galilee Society, Shefa-Amr, Israel
Tel Hai Academic College, Department of Environmental Science, Upper Galilee, Israel
Department of Natural Resources & Environment Management, University of Haifa, Haifa, Israel

Faissal Aziz National Center for Research and Studies on Water and Energy, Cadi Ayyad University, Marrakech, Morocco
Faculty of Sciences Semlalia, Laboratory of Water, Biodiversity and Climate change, Marrakech, Morocco

Abeer Albalawneh Director of Environment and Climate Change Directorate, National Agricultural Research Center (NARC), Albaqaa, Jordan

Khaled Bouchama Ecology and Environment Department, Khenchela University, Khenchela, Algeria
Biology Department, Faculty of Sciences, Badji Mokhtar Annaba University, Annaba, Algeria

R. Bresciani IRIDRA Srl, Florence, Italy

Marcos Bueno Centro de Innovación en Ingeniería Aplicada (CIIA), Departamento de Obras Civiles, Facultad de Ciencias de la Ingeniería, Universidad Católica del Maule, Talca, Chile

Florence Cattin Institute of Ecotechnics, US/UK, Santa Fe, NM, USA
Wastewater Gardens International, Santa Fe, NM, USA

Sarah den Haring GreenWater Environmental Water & Sanitation Solutions, Kilifi, Kenya

Mounir El Achaby Materials Science and Nanoengineering (MSN) Department, Mohammed 6 Polytechnic University (UM6P), Benguerir, Morocco

Abdeljalil El Ghadraoui Department of Chemistry, University of Florence, Florence, Italy

Ayoub El Ghadraoui Laboratory of Water, Biodiversity & Climate Change, Semlalia Faculty of Sciences, Cadi Ayyad University, Marrakech, Morocco
Department of Chemistry, University of Florence, Florence, Italy

Mohamed A. El-Khateeb Water Research & Polluted Control Department, National Research Centre, Dokki, Cairo, Egypt

Mohamed S. Gaballah College of Engineering (Key Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture), China Agricultural University, Beijing, People's Republic of China
National Institute of Oceanography and Fisheries, Alexandria, Egypt

Binita Gandhi Department of Civil Engineering, University of Victoria, Victoria, BC, Canada

Yoram Gerchman Oranim Academic College, Tivon, Israel
Department of Evolutionary and Environmental Biology, University of Haifa, Haifa, Israel

Amir Gholipour LEAF – Linking Landscape, Environment, Agriculture and Food, Institute Superior de Agronomia (ISA), University of Lisbon, Tapada da Ajuda, Lisbon, Portugal

Jianbin Guo College of Engineering (Key Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture), China Agricultural University, Beijing, People's Republic of China

Lamine Hafouda INRAA (Institut National de la Recherche Agronomique d'Algérie), Oued Smar, Algeria

Moushumi Hazra Department of Hydrology, Indian Institute of Technology, Roorkee, Uttarakhand, India

Samer Kalbouneh Water and Wastewater Treatment and Reuse Department, Biodiversity and Environmental Research Center (BERC), Nablus, Palestine

Jamidu H. Y. Katima Kampala International University in Tanzania, Dar es Salaam, Tanzania

Meera Keraliya Department of Environmental Science and Engineering, Marwadi University, Rajkot, Gujarat, India

Thammarat Koottatep Environmental Engineering and Management, Asian Institute of Technology, Bangkok, Thailand

Aness S. Mahenge Ardhi University, Dar es Salaam, Tanzania

Laila Mandi National Center for Research and Studies on Water and Energy, Cadi Ayyad University, Marrakech, Morocco
Faculty of Sciences Semlalia, Laboratory of Water, Biodiversity and Climate change, Marrakech, Morocco

Mona S. M. Mansour Analysis & Evaluation Department, Egyptian Petroleum Research Institute, Nasr City, Cairo, Egypt

N. Martinuzzi IRIDRA Srl, Florence, Italy

F. Masi IRIDRA Srl, Florence, Italy

Rwaichi Minja University of Dar es Salaam, College of Engineering and Technology, Dar es Salaam, Tanzania

Atif Mustafa Department of Environmental Engineering, NED University of Engineering and Technology, Karachi, Pakistan

Mark Nelson Institute of Ecotechnics, US/UK, Santa Fe, NM, USA
Wastewater Gardens International, Santa Fe, NM, USA

Agnes Nyomora University of Dar es Salaam, Department of Botany, Dar es Salaam, Tanzania

Jorge Olave Centro de Investigación y Desarrollo en Recursos Hídricos (CIDERH), Universidad Arturo Prat, Iquique, Chile

Naaila Ouazzani National Center for Research and Studies on Water and Energy, Cadi Ayyad University, Marrakech, Morocco
Faculty of Sciences Semlalia, Laboratory of Water, Biodiversity and Climate change, Marrakech, Morocco

Anne H. Outwater Muhimbili University of Health and Allied Sciences, Dar es Salaam, Tanzania

Hirendrasinh Padhiyar Department of Environmental Science and Engineering, Marwadi University, Rajkot, Gujarat, India

Chongrak Polprasert Department of Civil Engineering, Thammasat School of Engineering, Thammasat University, Bangkok, Thailand

Tatchai Pussayanavin Environmental Engineering and Management, Asian Institute of Technology, Bangkok, Thailand
Faculty of Science, Ramkhamhaeng University, Bangkok, Thailand

A. Rizzo IRIDRA Srl, Florence, Italy

Ayman N. Saber Pesticide Residues and Environmental Pollution Department, Central Agricultural Pesticide Laboratory, Agricultural Research Center (ARC), Giza, Egypt
National Engineering Laboratory for Industrial Wastewater Treatment, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China
University of Chinese Academy of Sciences, Beijing, China

Noama Shareef Water Policy Officer at the European Water Association EWA, Bonn, Germany

Nitin Kumar Singh Department of Environmental Science and Engineering, Marwadi University, Rajkot, Gujarat, India

Alexandros Stefanakis Laboratory of Environmental Engineering and Management, School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece
EURECA-PRO – The European University on Responsible Consumption and Production, Chania, Greece

Arti Thanki Department of Environmental Science and Engineering, Marwadi University, Rajkot, Gujarat, India

Rocío Tíjaro-Rojas Carrera de Ingeniería Civil Ambiental, Facultad de Ingeniería y Arquitectura, Universidad Arturo Prat, Iquique, Chile

Davide Tocchetto Institute of Ecotechnics, US/UK, Santa Fe, NM, USA
Wastewater Gardens International, Santa Fe, NM, USA

Rob Van Deun Thomas More University of Applied Sciences, Geel, Belgium

Frank van Dien ECOFYT, Boxtel, The Netherlands

Ismael Vera-Puerto Centro de Innovación en Ingeniería Aplicada (CIIA), Departamento de Obras Civiles, Facultad de Ciencias de la Ingeniería, Universidad Católica del Maule, Talca, Chile

Manish Yadav Central Mine Planning and Design Institute Limited, Bhubaneswar, India

Abdallah Zacharia Muhimbili University of Health and Allied Sciences, Dar es Salaam, Tanzania

Fouad Zouhir Unité Assainissement et Environnement, Université de Liège, Arlon, Belgium

Chapter 1
Constructed Wetlands as a Green and Sustainable Technology for Domestic Wastewater Treatment Under the Arid Climate of Rural Areas in Morocco

Laila Mandi, Naaila Ouazzani, and Faissal Aziz

Abstract The aim of this chapter is to demonstrate the applicability and the adaptation of constructed wetland (CWs) eco-technology for the treatment of domestic wastewater, especially in rural areas under the arid climate of Morocco. As most rural areas in Morocco are suffering from water and soil pollution, there is a potential health risk posed by untreated wastewater discharge into the environment. Lack of sanitation in these regions, where technical and financial resources are usually limited, has a negative impact on the quality of life of the rural population and their water resources. Developing treatment techniques adapted to this context is very challenging, taking into account the social, technical, and financial capacities of rural areas. Green and sustainable technologies such as CWs have several inherent advantages compared to conventional treatment systems, including low capital costs, less infrastructure, lower operating costs, simplicity of construction, and ease of operation. CWs under different sanitation typologies proved an efficient wastewater treatment method in real applications in the rural villages of Morocco and could be considered as an efficient domestic wastewater treatment solution under arid conditions to promote environmental protection and wastewater reuse.

Keywords Arid climate · Constructed wetlands · Domestic wastewater · Rural sanitation · Reuse · Morocco

L. Mandi (✉) · N. Ouazzani · F. Aziz
National Center for Research and Studies on Water and Energy, Cadi Ayyad University, Marrakech, Morocco

Faculty of Sciences Semlalia, Laboratory of Water, Biodiversity and Climate change, Marrakech, Morocco
e-mail: mandi@uca.ac.ma

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_1

1.1 Introduction

Morocco is located in arid areas and has been faced with several water management problems. The arid climate, the heterogeneity of water resources distribution, and the repetition of drought related to climate change reduce the potential of water resources [1]. In spite of the major effort on water availability and water supply for the growing population in Morocco, and despite a legislative, and organizational upgrade of the management of the water sector, a big delay has to be caught up in the sanitation and wastewater treatment, particularly in rural areas. The discharge of wastewater increases the threat of water pollution and reduces the availability and quality of water resources [2]. The high costs of conventional treatment processes have led national authorities to search for creative, efficient, and environmentally sound ways to control water pollution. Green and sustainable technologies such as constructed wetlands (CWs) could be considered as a useful tool to manage wastewater economically and effectively in rural areas in Morocco.

CWs have been applied in a number of countries with hot and dry climates [3–5]. They can be applied as primary, secondary, or tertiary treatment, allowing the degradation of the organic pollutants and the removal of pathogenic microorganisms, so that wastewater can be recycled for irrigation and domestic use and hence reduce the pressure on the freshwater resources [6]. Moreover, the big challenge is to overcome all the socio-economic and institutional barriers that are hindering their development [3].

This chapter presents the context and obstacles to the implementation of wastewater treatment facilities in the Moroccan rural areas and the status of CWs, from experimental research to full-scale projects, as a reference and exemplary design. The treatment performances of CWs and the pollutant removal mechanisms within the systems are described, as well as their design and operation, and their adaptability to the arid climate. This chapter demonstrates that CWs can be considered as an efficient domestic wastewater treatment solution in rural areas, either as a hybrid system or in combination with other green processes, under arid conditions, to promote environmental protection and wastewater reuse.

1.2 Current Status of Sanitation in Moroccan Rural Areas

In Morocco, the rural population is estimated at 13.4 million inhabitants, distributed in 1298 rural municipalities, with around 33,000 villages [7]. Significant progress has been made in the provision of drinking water to the rural population by the Moroccan government. Unfortunately, this progress has not been accompanied by a similar effort in terms of sanitation [8]. Most of the rural centers are established without a development plan in the majority of cases and suffer from a lack of basic sanitation infrastructure. According to the High Commission for Planning [7], the sanitation facilities' access rate in these areas is only about 11%, considering just improved systems (septic tanks and latrines), while the population connected to the public sewerage system represents 1.7%. This is common worldwide in the rural population where only 9% is connected to sewerage systems [9]. The total production of wastewater in rural areas is estimated to 125 million m^3/year [10]. Sanitation facilities are rare in rural areas and, if they exist, are rudimentary and generally limited to latrines with storage pits, septic tanks, simplified networks, or cesspools made by the local population lacking adequate technical support to have a processing system of minimum performance, plus a few pilot rural ecological sanitation systems. Resulting wastewaters are discharged directly into the environment and gravity fed into Chaâba (dry bed of a river), where they are infiltrated or used for irrigating small agricultural parcels if they exist. Sludge from latrines and septic tanks, when emptied, is either discharged into landfills or discharged into the natural environment. The excreta of households without toilets are released into the environment or mixed with manure [11]. Thus, the state of sanitation can be described as follows [10]:

- 88% of domestic wastewater is discharged directly into the environment,
- 38% of villages is equipped with excreta disposal devices,
- < 10% of rural municipalities is connected to the collective sewerage system,
- < 3% of rural communities has access to the collective wastewater treatment plant.

The direct discharge of wastewater into the environment (Fig. 1.1) contributes widely to the degradation of the landscape, the contamination of surface and groundwater, and the spread of waterborne diseases. Thus, more than 800 children die every year due to preventable water and sanitation-related diarrhea diseases in Morocco [12].

It therefore becomes imperative to [13]:

- Urgently upgrade rural centers established without a development plan to improve the living conditions of populations, including sanitation and the implementation of wastewater treatment plants,

Fig. 1.1 Discharge of wastewater in some rural areas of Morocco.

- Strengthen actions on the determinants of health (access to drinking water, sanitation and purification, health education and global education, accessibility, etc.) by targeting in priority disadvantaged regions and poor or vulnerable populations,
- Mandatory linking drinking water supply to liquid sanitation and the implementation of appropriate micro and macro wastewater treatment plants.

1.3 Barriers for Wastewater Treatment in Moroccan Rural Areas

Like many developing countries, achieving access to sanitation facilities still pose major challenges in rural areas of Morocco. The main barriers that limit the access to sanitation infrastructure in small communities are:

- **Habitat dispersal.** In rural areas, most of the villages are "split up" into several groups of dwellings, which can go as far as a total dispersal of the habitat. Under these conditions, any public sanitation service system could only be realized at the cost of large investments and high operating and maintenance costs.
- **Mountain topography.** According to the sites and their difficulties of access, the mountain edifices are in fact completely broken, from a physical point of view, with the nearest valleys, which leads to a break in communication, a break in supply, a rupture at the level of public structures. This rupture is reinforced by the fact that these places are inaccessible to vehicles, which complicates their refueling as well as their maintenance.
- **Poverty.** The low socio-economic status of the rural population hinders access to adequate sanitation. Poverty is widespread in rural areas where interventions related to water supply and sanitation generally takes place, therefore most beneficiaries are poor. Poorer people in recipient communities generally also benefit from improved water supply and sanitation. But the poorest and most marginalized communities generally have less access to and do not benefit from national programs.
- **Management obstacles.** Most of rural areas lack real expertise and technical assistance, as well as public and private partners. In addition, local decision-makers don't have the capacity to see problems globally and in the long-term, without focusing exclusively on technical vision, but integrating all administrative, economic, geographical and environmental issues. The multiplicity of stakeholders and the lack of coordination, do not promote the rational development of the sanitation sector. In addition, there is a low budget priority accorded to sanitation facilities compared to other development areas, including water supply.
- **Investment weaknesses.** Sanitation is a huge financial burden for small communities in Morocco. While many of them are already in debt, they are facing new obligations requiring heavy short-term investments. If half of the pollution produced is released to the environment, the amounts to be spent to achieve the objectives are considerable.

1.4 Sanitation Strategic Action Plans in Morocco

Wastewater sanitation in rural areas is one of the basic services contributing to ensuring health, comfort, and ensuring appropriate life for the population. The Moroccan government has made extensive efforts in this sector through the establishment since 2005 of the 'National Liquid Sanitation and Wastewater Treatment Program'(PNA), whose main objective is the improvement and development of the sanitation sector across the kingdom. The socio-economic impact expected from this program concerns the improvement of citizens' living environment, improving hygiene and health, creating jobs, and promoting sustainable tourism. This program has been tremendous progress in terms of catching up with the delay in the Moroccan sanitation sector. Nevertheless, the PNA has given high priority to sanitation in urban areas at the expense of communities in rural areas. In 2013, the Moroccan government has launched the second version of PNA adapted to the rural communities called 'National Liquid Sanitation Program in Rural Areas' (PNAR) to assist local authorities technically and financially to fulfill their role in the management of sanitation facilities. The PNAR objectives for 2040 are defined as follows [1]:

- Eradicate defecation in nature,
- Achieve 100% rate of equipping rural households with sanitation facilities,
- Achieve a 50% purification rate of wastewater.

The PNAR consists of carrying out liquid sanitation projects, ensuring the collection, transfer and treatment of wastewater depending on the structure of the rural centers and villages (size, density, etc.). Three categories of sanitation installations are defined: a collective system for the administrative centers of rural communes and villages with more than 1500 inhabitants; semi-collective system for villages of 500–1500 inhabitants; individual system for villages of less than 500 inhabitants. In order to facilitate decision-making for the choice of the adapted system for each category, technical guides will be drawn up and made available to rural municipalities [1]. Recently, to optimize and rationalize the efforts of the various stakeholders involved in the liquid sanitation sector, a catch-up program is developed. Thus, a consolidated 'National Sanitation Program' (PNAM) was born; this is a new program involving the National Liquid Sanitation and Wastewater Treatment Program, the National Liquid Sanitation Program in Rural Areas, and the National Program for the Reuse of Treated Wastewater [8]. The challenge now is to go beyond the basic liquid sanitation to extend toward the treatment, reuse, and recovery of water, according to the principle of the circular economy. This program, which aims to capitalize on the achievements of the various programs, will allow better planning of wastewater treatment plants according to reuse needs and will allow the rural area to be integrated into sanitation program and ensure the financing of the various projects in an integrated manner. The PNAM which will cover the period 2020–2040 has the following main objectives [8]:

- Achieve a rate of >90% as connection to sewerage in urban areas,
- Reduce pollution caused by wastewater to >80% in urban areas,

- Achieve a rate of 50% in 2030 and 80% in 2040 as a connection to sewerage in rural areas,
- Reduce pollution caused by wastewater to 40% in 2030 and 80% in 2040 in rural areas.

1.5 Application of Constructed Wetlands for Wastewater Treatment in Rural Areas

1.5.1 Overview of Pilot-Scale CWs for Domestic Wastewater Treatment in Morocco

The first experiments on the application of CWs were carried out under the arid climate of Morocco in 1986–1987 [14] with the main goal to study their feasibility to treat domestic wastewater in rural small communities for potential reuse in agriculture without sanitary risks. Several experiments were carried out at pilot scale at the University Cadi Ayyad in Marrakech (Morocco) to test the ability of such green eco-technologies to treat both domestic and urban wastewaters using different system designs.

The initial investigations were carried out in horizontal flow CWs (HF-CWs) consisted in two lined ponds planted with floating macrophytes (*Eichornia crassipes*; *Lemna gibba)* and tested for primary and secondary treatment of domestic wastewater, respectively [14, 15]. These experiments proved the adaptation of HF-CW to the arid climate of Morocco and showed their efficiency to remove the organic load, nutrients and sanitary parameters. However, two major problems were raised and should be overcome using HF-CW under this arid climate; the high water losses by evapotranspiration, which can reach up to 60% in the summer period, and the spread of mosquitoes that limits the adoption of such systems under the arid climate [16].

Vertical flow constructed wetlands (VF-CWs) were developed in 1994 in Morocco for primary treatment of urban wastewater at pilot scale using a local sandy soil as main substrate and a drainage layer of gravel at the bottom. The system was planted with emergent macrophytes such as *Typha latifolia* latifolia, *Juncus subulatus* and *Arundo donax* [17–19]. The authors proved that the VF-CWs are successful in removing organic compounds, suspended solids, nutrients and heavy metals. Nevertheless, their efficiency to remove pathogens was weak with sanitary risks for potential reuse in agriculture [19, 20].

The horizontal subsurface flow CW (HSSF-CW) type was evaluated by El Hamouri et al. [21] in Rabat (Morocco) as secondary treatment after an anaerobic reactor. The study demonstrated the high ability of HSSF-CW to remove organic matter and nutrients from pretreated wastewater; however, the system was not able to remove fecal bacteria indicators. These lead researchers to investigate the combination of VF-CW and HSSF-CW systems. El Hamouri et al. [22] developed a hybrid CW (HCW) pilot plant in Rabat (Morocco), which combines a VF-CW, HSSF-CW and sand filter for primary, secondary and tertiary treatment of domestic wastewater, respectively. The system has proven its efficiency to produce an effluent quality suitable for direct discharge or for irrigation of forage crops, cereals and fruit trees according to WHO guidelines [23].

Even though several researches have demonstrated the appropriateness of CW eco-technology to treat domestic wastewater under the arid climate of Morocco, the implementation of full-scale CWs projects is still underdeveloped in Morocco. Only few successful projects have been developed in rural areas and are presented in the next section.

1.5.2 Full-Scale CWs for Domestic Wastewater in Moroccan Rural Areas

Case Study 1 Tidili Mesfioua Hybrid Constructed Wetland (VF-CW + HSSF-CW).

According to Vymazal [24] and Chen et al. [25], Hybrid Constructed Wetlands (HCWs) combining VF-CW and HSSF-CW are probably the most frequently used HCWs for treatment of municipal sewage particularly in Europe and Asia. Nevertheless, there are only few studies using HCWs in rural sanitation for small communities [4, 26].

This case study presents the first full-scale HCW implemented in Morocco in a small rural community named Tidili Mesfioua within the region of Marrakech for treatment and reuse of domestic wastewater (Fig. 1.2). The HCW was built in 2014 for treating the wastewater from 1844 inhabitants and has been in operation since then. The project was carried out with funding from the US Agency for International Development (USAID) with the contribution of stakeholders. This HCW is also the first plant in Morocco managed by a rural local NGO called Tissilte association for development (ATD).

The wastewater treatment plant consists of a lifting station, a storage tank with a self-priming siphon, to obtain a hydraulic batch mode for feeding a first stage of three VF-CWs (four feeding batches per day) working in parallel, a second stage of two HSSF-CWs connected also in parallel (Fig. 1.2). Each bed has a slope of 1% and is planted with *Phragmites australis* with an initial density of 4 plants/m^2 [5]. The main design criteria of the Tidili Mesfioua HCW are presented in Table 1.1.

Treated wastewater is discharged to a tank where it is temporarily stored for potential reuse in crop irrigation. Thanks to the collaboration between the University Cadi Ayyad (Marrakech) and the association ATD, a regular monitoring of the HCW is ensured to determine its purification performance and to assess the quality of water to be reused in agriculture. Several water quality parameters including pH, electrical conductivity (EC), dissolved oxygen (DO), total suspended solids (TSS), biological oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), fecal coliforms (FC), *Escherichia coli* (*E. coli*) and

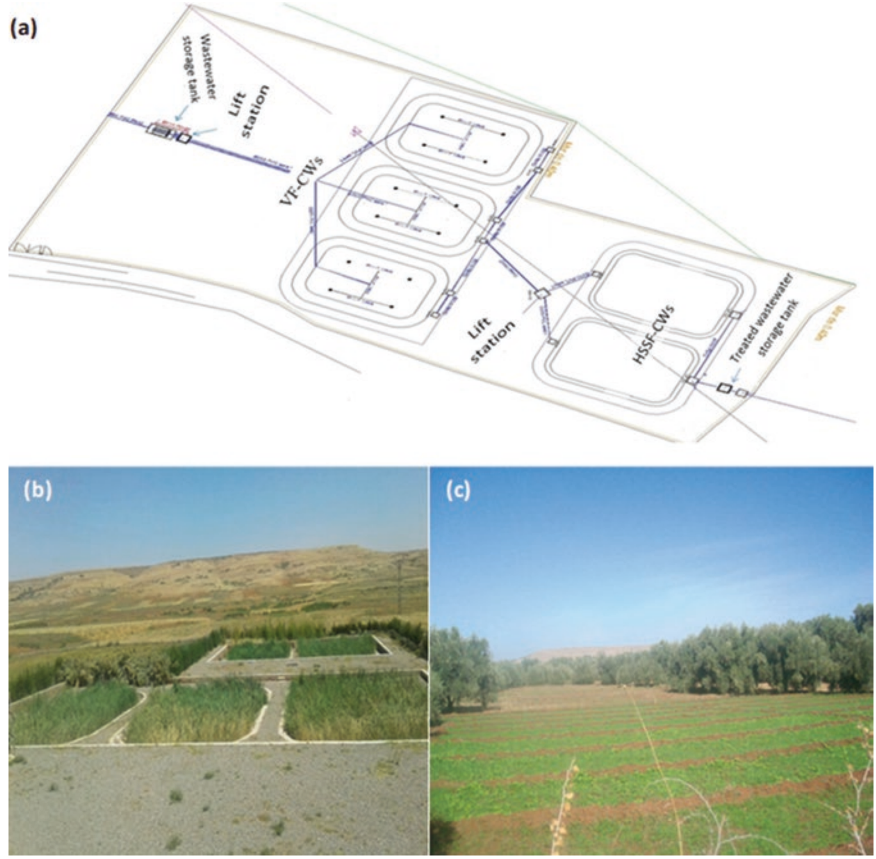


Fig. 1.2 (**a**) Schematic layout of the Tidili Mesfioua Hybrid Constructed Wetland, (**b**) aerial view of the plant, and; (**c**) field area irrigated with treated wastewater

helminth eggs (HE) are monitored at the inlet and the outlet of the HCW according to Standard Methods [5]. The obtained results are presented in Table 1.2.

The main average removal percentages of TSS, BOD_5, COD, TN and TP are 95%, 94%, 91%, 67% and 62%, respectively. Tidili Mesfioua HCW in its actual design combining both vertical and horizontal subsurface flow CWs was very effective in the removal of organic matter and suspended solids. TSS removal is mainly the result of physical processes such as sedimentation and filtration [29]. Fast decomposition processes are responsible for COD and BOD_5 high removal rates [30]. The root zone of *Phragmites Australis* is also of particular importance in removing biodegradable organic material and provides a substrate for attached bacteria which are responsible for the biodegradation of organic material [31].

The main removal mechanisms of Total Nitrogen are ammonification and subsequent nitrification occurred in VF-CW, and denitrification which occurs in HSSF-CW units, plant uptake and export through biomass harvesting [6]. The removal of phosphorus is done by adsorption-precipitation reactions within the

Table 1.1 Design criteria's of Tidili Mesfioua Hybrid Constructed Wetland

Parameter	Unit	Value
Person equivalent	EH	1844
Type of wastewater	–	Domestic
Flow	m^3/d	66
Pretreatment	–	Bar screen
Concept design	–	Hybrid constructed wetland -first stage: 3VF-CWs (primary treatment) -second stage: 2 HSSF-CWs (secondary treatment)
Total area	m^2	3000
Hydraulic loading rate:	$m^3/m^2/d$	
VF-CW		0.5
HSSF-CW		0.75
Dimensions	m	
VF-CW		Length: 13, width: 10, depth: 0.9
HSSF-CW		Length: 11, width: 8, depth: 0.6
Filling media		50 cm of fine gravel (Ø: 2/8 mm)
VF-CW		20 cm of coarse gravel (Ø: 3/20 mm)
		20 cm of pebble (Ø: 60/100 mm)
HSSF-CW		60 cm fine gravel (Ø: 2/8 mm)
Organic loading rate	g BOD_5/m^2/day	
VF-CW		194
HSSF-CW		28

Table 1.2 Treatment performance of Tidili Mesfioua HCW (mean ± standard deviation)

Parameter	Raw wastewater	Treated wastewater	Removal (%)	Admissible limits for direct discharge [27]	Admissible limit for wastewater reuse [28]
pH	7.61 ± 0.02	7.54 ± 0.01	–	–	6.5–8.4
EC (mS/cm)	1.72 ± 0.04	1.81 ± 0.04	–	–	12
DO (mg/L)	0.64 ± 0.1	2.73 ± 0.5	–	–	–
TSS (mg/L)	429.75 ± 17.66	22.55 ± 2.64	95	150	100
BOD_5 (mg/L)	338.50 ± 16.91	18.23 ± 1.78	94	120	–
COD (mg/L)	683.23 ± 20.36	52.95 ± 2.29	91	250	–
TN (mg/L)	44.11 ± 0.79	16.43 ± 0.47	67	–	–
TP (mg/L)	8.39 ± 0.15	3.13 ± 012	62	–	–
FC (logCFU/100 mL)	6.77	2.54	4.25	–	≤3
E. coli (logCFU/100 mL)	6.85	2.55	4.36	–	–
HE (egg/L)	42	0	100	–	≤1

HCW substrate media, uptake by plants, and export through biomass harvesting [6, 32]. Concerning the sanitary performance, the Tidili Mesfioua HCW showed a very high efficiency in removing fecal coliforms (4.25 logCFU/100 mL), *E. coli* (4.36 logCFU/100 mL) and helminth eggs (100%). Several mechanisms such as natural die-off, sedimentation, filtration, and predation are responsible for the abatement of fecal bacteria indicators and pathogen in the constructed wetlands [6]. Thus, wastewater composition, type of macrophyte, hydraulic regime, hydraulic retention time, filter media, UV action, temperature, oxidation and pH, are probably the main factors influencing fecal indicators and pathogen removal by the HCW [6, 33].

Based on the obtained results, the Tidili Mesfioua hybrid constructed wetland was a successful method for rural sanitation and provides effective treatment performance in terms of removal of organic matter, nutrients, fecal indicator bacteria, pathogen, and helminth eggs. The treated wastewater fulfilled the Moroccan standards on irrigation water quality for feed crops [34] and WHO recommendations [23]. Treated wastewater by this HCW is reused for different purposes like olive trees and alfalfa irrigation.

Case Study 2 Asselda constructed wetland (VF-CW+ Pond).

It was noticed that the integration of CW units with other treatment systems in rural sanitation is popular around the world [4]. This case study presents a full-scale VF-CW followed by maturation pond implemented in the Asselda village located in the province of Al-Haouz (Morocco). The plant was built in 2015 for treating the domestic wastewater from 1260 inhabitants and has been in operation since then. The project was carried out with funding from the Drosos Foundation (Zurich) in collaboration with AMSED association and contribution of the village NGO and the stakeholders. The main design criteria of this plant are presented in Table 1.3.

The wastewater treatment plant consists of a lifting station, a storage tank with a self-priming siphon, in order to obtain a hydraulic batch mode for feeding the three vertical flow constructed wetlands (VF-CW) working in parallel. The VF-CWs are planted by *Phragmites australis* and followed by a maturation pond as secondary treatment (Table 1.3, Fig. 1.3). Treated wastewater is discharged to a tank where it is temporarily stored for fruits tree irrigation. The Asselda wastewater treatment plant is managed by the national office of water and electricity (ONEE), operator in charge of rural sanitation in Morocco.

The global performance of this plant is presented in Table 1.4. The Asselda wastewater treatment plant showed high performance in the removal of TSS (93%), BOD5 (96%), and COD (88%); the efficiency of the plant to remove nutrients was moderate for TN (55%) and TP (55%). The system proved to be less effective in reducing the fecal contamination indicator bacteria, with a mean removal rate of 1.85 logCFU/100 mL. Even though the maturation pond is normally designed to remove fecal coliform and pathogens, including bacteria, viruses and helminth eggs [35], its efficiency in Asselda plant was poor. Probably, adding another pond could allow for higher performance in fecal coliforms removal.

Table 1.3 Design criteria's of Asselda wastewater treatment plant (VF-CW+ Pond)

Parameter	Unit	Value
Person equivalent	EH	1260
Type of wastewater	–	Domestic
Flow	m^3/d	63
Pretreatment	–	Bar screen
Concept design	–	3VF-CWs in parallel (primary treatment) 1 maturation pond (secondary treatment)
Total area	m^2	2500
Hydraulic loading rate:	$m^3/m^2/d$	
VF-CW		0.3
V		
Dimensions	m	
VF-CW		Length:17, width: 12, depth: 0.9
Filling media VF-CW	–	50 cm of fine gravel (Ø: 2/8 mm). 20 cm of coarse gravel (Ø: 3/20 mm), 20 cm of pebble (Ø: 60/100 mm)
Organic loading rate	g BOD_5/m^2/day	65
Secondary treatment		Maturation pond
	m m^3 d	Length: 20.5, width: 10.2, depth: 1.2 Volume: 251.6 Residence time: 5

Thus, the treated domestic wastewater from the Asselda plant was in compliance with the Moroccan standards for direct discharge. The average content of fecal coliforms obtained at the outlet of this plant is still higher than 1000 CFU/100 mL, the limit value of the B category in Moroccan standards of water quality for irrigation [34]; therefore, the effluent is reused mainly for the irrigation of tree plantations. This rural sanitation typology combining VF-CW as primary treatment with a maturation pond as secondary treatment, investigated for the first time in Morocco, showed promising performance and could be adopted by small communities in rural areas.

Case Study 3 Talat Marghen wastewater treatment plant (Septic tank+MSL + HSSF-CW).

Rural sanitation systems comprising a septic tank followed by CW units are also very common worldwide [4]. Most of the studied systems use septic tank as pretreatment followed by HSSF-CW [36, 37]; HSSF-CW and pond [38]; VF-CW and pond [38] or VF-CW and HSSF-CW [39]. Nevertheless, the application of a sanitation typology combining a septic tank followed by a Multi-Soil-Layering (MSL) system, then HSSF-CWs has not been yet explored to the best of our knowledge. Accordingly, this case study presents a full-scale wastewater treatment plant composed of a septic tank, followed by MSL system, and a HSSF-CW, implemented in a small village named Talat Marghen located in the province of Al-Haouz (Morocco). The plant was built in 2016 for treating the domestic wastewater of 600 inhabitants and has been in operation since then. The project was carried out with

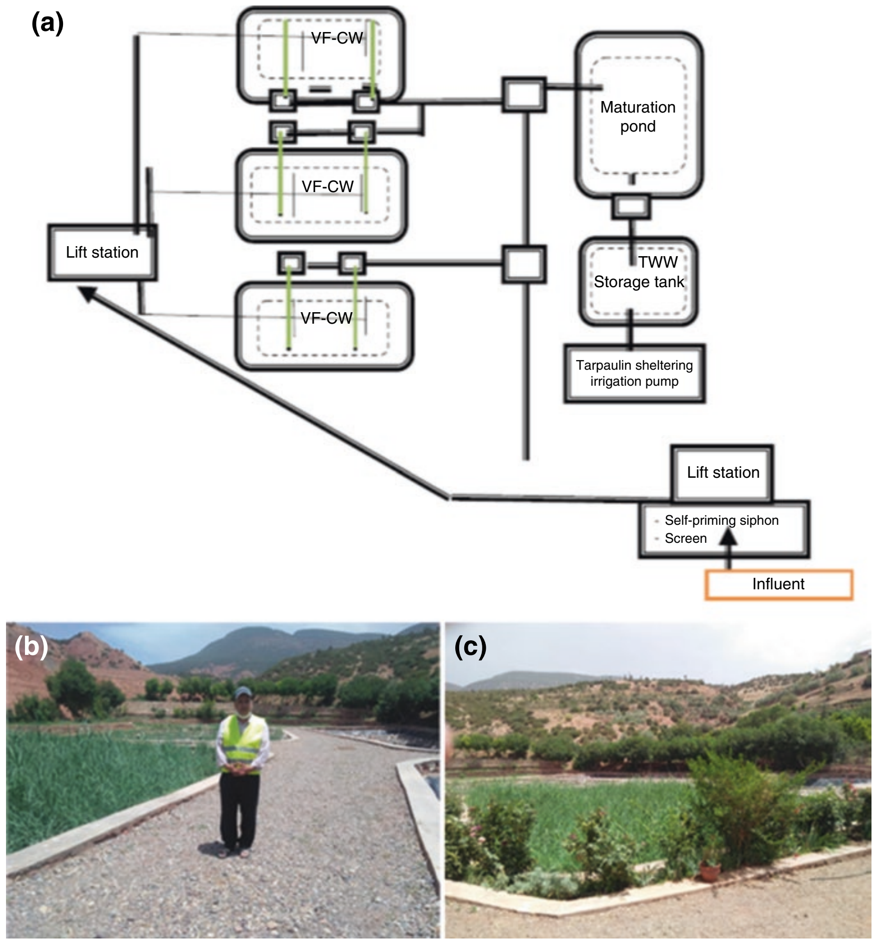


Fig. 1.3 (**a**) Schematic layout of the Asselda village's wastewater treatment plant; (**b**) aerial view of the plant and; (**c**) irrigated trees area.

funding from the National office of Drinking Water and Electricity and the contribution of the stakeholders. The main design criteria of the Talat Marghen plant are presented in Table 1.5.

The Talat Marghen village wastewater treatment plant is composed of septic tank followed by two Multi-Soil-Layering systems in parallel, then two HSSF-CWs working in parallel as one stage (Table 1.5, Fig. 1.4). The HSSF-CWs are planted by *Typha Latifolia* with an initial density of 4 plants/m^2. Treated wastewater is discharged to a storage tank where it is temporarily stored for fruits tree irrigation. The plant is managed by the village association.

The global performance of the Talat Marghen wastewater treatment plant is presented in Table 1.6. The system presented high performance in the removal of TSS (97%), BOD_5 (98%), COD (94%), TN (94%) and TP (91%). The removal of

Table 1.4 Treatment performance of Asselda village wastewater treatment plant (Mean ± standard deviation)

Parameter	Raw wastewater	Treated wastewater	Removal (%)	Admissible limits for direct discharge [27]	Admissible limit for wastewater reuse [28]
pH	7.77 ± 0.05	8.04 ± 0.03	–	–	6.5–8.4
EC (mS/cm)	5.6 ± 0.25	4.97 ± 0.013	–	–	12
TSS (mg/L)	647 ± 15.36	41 ± 2.34	93	150	100
BOD_5(mg/L)	860 ± 17.81	31 ± 1.28	96	120	–
COD (mg/L)	1573 ± 30.46	180 ± 4.25	88	250	–
TN (mg/L)	58.15 ± 0.83	25.85 ± 0,18	55	–	–
TP (mg/L)	13.09 ± 0.12	5.83 ± 0.125	55	–	–
FC (logCFU/100 mL)	7.17	5.32	1.85	–	≤3
HE (egg/L)	55	0	100	–	≤1

Table 1.5 Design criteria's of Talat Marghen wastewater treatment plant (ST + MSL + HSSF-CW)

Parameter	Unit	Value
Person equivalent	EH	600
Type of wastewater	–	Domestic
Flow	m^3/d	16.35
Pretreatment	–	Bar screen + septic tank (volume: 49 m^3)
Concept design	–	2 MSLs in parallel 2 HSSF-CWs in parallel
Total area	m^2	218
Hydraulic loading rate	$m^3/m^2/d$	
MSL HSSF-CW		0.25 0.13
Dimensions	m	
MSL HSSF-CW		Length: 8, width: 4.25, depth: 2.47 Length:10, width: 6, depth: 0.6
Filling media MSL HSSF-CW		SMLs (mixture of local soil (70%), sawdust (10%), charcoal (10%) and metal iron (10%)) arranged in a brick-layer-like pattern separated by gravel layers (Ø: 3/5 mm). 60 cm fine gravel (Ø: 2/8 mm)
Organic loading rate	g BOD_5/ m^2/day	
MSL HSSF-CW		163.87 22.23

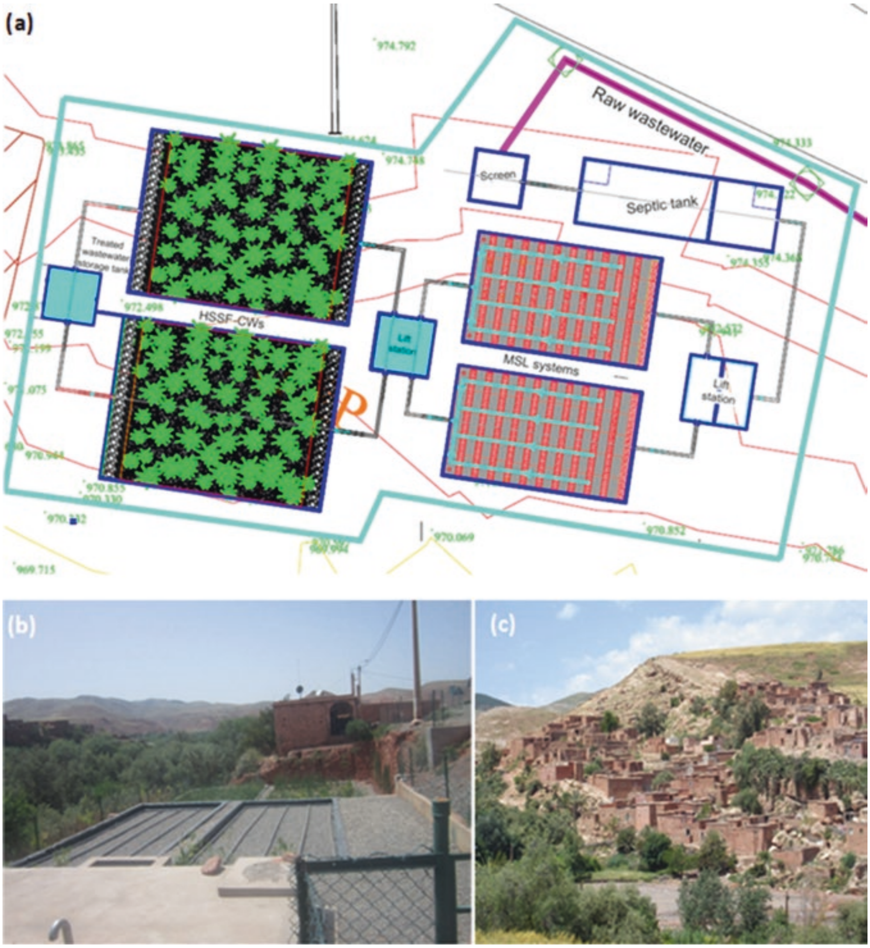


Fig. 1.4 (**a**) Schematic layout of the Talat Marghen village wastewater treatment plant; (**b**) aerial view of the plant and; (**c**) village view

suspended solids is mainly realized by sedimentation and filtration on the filter media of the MSL and CW units [6, 40, 41]. The reduction of organic matter is realized, particularly through microbiological degradation under aerobic conditions in the pores of the MSL system [42]. Other mechanisms such as filtration and adsorption can also contribute to the removal of organic matter in MSL and CWs units [43, 44]. The high removal efficiency for TN was due to the ability of the MSL media to adsorb ammonium and to the co-existence of aerobic and anaerobic conditions inside the MSL system that induce nitrification/denitrification processes [40]. In addition, denitrification, plant uptake and export through biomass harvesting are more dominant mechanisms for TN removal in the CW units [6]. TP removal is very high due to the adsorption of orthophosphates on the Fe and Al hydroxides in the filter media of MSL and CW units; and precipitation, particularly with iron metal

Table 1.6 Treatment performance of the Talat Marghen CW plant (mean ± standard deviation)

Parameter	Raw wastewater	Treated wastewater	Removal (%)	Admissible limits for direct discharge [27]	Admissible limit for wastewater reuse [28]
pH	7.71 ± 0.04	7.33 ± 0.02	–	–	6.5–8.4
EC (mS/cm)	1.65 ± 0.02	1.75 ± 0.13	–	–	12
DO (mg/L)	0.51 ± 0.11	3.03 ± 0.40	–	–	–
TSS (mg/L)	1368 ± 15.26	30.57 ± 2.64	97	150	100
BOD_5(mg/L)	962 ± 16.91	20.05 ± 1.78	98	120	–
COD (mg/L)	2219 ± 20.36	118 ± 2.29	94	250	–
TN (mg/L)	221.87 ± 0.79	12.32 ± 0,47	94	–	–
TP (mg/L)	73.73 ± 0.15	6.81 ± 012	91	–	–
FC (logCFU/100 mL)	7	2.4	4.5	–	≤3
HE (egg/L)	53	0	100	–	≤1

added to the soil mixture layer of the MSL system, plant uptake and export through biomass harvesting [6, 40, 45].

This rural sanitation typology combining Septic tank, MSL and HSSF-CW was also very effective in reducing the levels of indicator bacteria (fecal coliforms) and helminth eggs, with removal rates of 4.5 logCFU/100 mL and 100%, respectively. Sedimentation, filtration, adsorption, natural die-off, microbial inactivation and predation (carried out by protozoa and metazoa) are the main mechanisms involved in bacteria removal from wastewater treatment technologies based on filtration process in MSL and CW systems [6, 40, 46].

Considering the overall performances achieved by the Talat Marghen wastewater treatment plant, the effluent quality has always satisfied the admissible limits for direct wastewater discharge recommended by the Moroccan standards. Moreover, the rural sanitation typology presented in this case study, which combines the septic tank followed by Multi-Soil-Layering and subsurface horizontal flow constructed wetland, shows the disinfection role of the HSSF-CW in this plant. Latrach et al. [40, 47] have indicated in their studies that the MSL with vertical flow CW alone couldn't eliminate fecal bacteria. The use of HSSF-CW here guarantees the coliform level recommended for treated wastewater reuse in irrigation.

1.6 Future Considerations on the Application of CWs in Rural Areas under Arid Climate

From these recent full-scale projects, the hybrid constructed wetland plant showed the higher performance and the best quality of treated water, better than when it was combined with a pond. It showed also very interesting sanitary removal performance when it was used as tertiary treatment for example after MSL filter. If we calculate the required surface per person equivalent for each sanitation typology, we could notice that the three case studies give similar performances concerning the elimination of organic matter and nutrients; but the required surface is more important when using HCWs (1.62 m^2/pe) and VF-CW + Pond (1.19 m^2/pe) systems. However, the sanitary performance of the HCW is still higher and the quality of treated water is perfectly fitting with the Moroccan regulations and WHO guidelines for water reuse in irrigation.

Similar sanitary performances were obtained with the combination of Septic tank+MSL + HSSF-CW with less required surface (0.47 m^2/pe). Thus, the adoption of pretreatment (septic tank) in Talat Marghen wastewater treatment plant contributes to reduced area requirements and less clogging problems. Pretreatment systems such as a septic tank, anaerobic pond, sedimentation tank, or UASB reactor are often adopted in rural sanitation for the removal of TSS and organic matter prior to CWs [37, 48–52]. The application of the CWs at full scale and the successful adaption and the high performance assessed in such treatment systems constitute a very good demonstration for both decision makers in rural communities and for the operators that are in charge of the implementation of wastewater treatment plants in rural areas in Morocco. These demonstrations are convincing about the reliability of such green technologies and their adaptability to the socio-economic context of the rural environment. In addition, these best practices constitute a good tool for the technical staff of either rural communities or operators to learn how to handle and manage these ecological engineering systems. Despite the fact that the operation and maintenance of nature-based technologies is relatively simple, training and technical assistance are essential to build the capacity of local NGOs and rural municipalities' staff to successfully manage the wastewater treatment plant.

Furthermore, the treated wastewater by different rural sanitation designs has been reused in the irrigation of surrounding parcels. Farmers are aware that the reuse of wastewater treated by such simple, economic, environmentally friendly, odorless, and easy to handle eco-technologies could be a good alternative to the discharge of raw wastewater into the river or in receptor media. However, a big effort is still needed in the future to raise the acceptance of all the farmers given the opportunity to use treated wastewater instead of surface or ground water for edible food, if the treated water fits well with the Moroccan standard limits and WHO guidelines.

Another issue to be addressed in the future is the plant biomass valorization generated by the constructed wetland systems via harvesting parts of *Phragmites australis* or *Thypha latifolia*. Locally, some handy craft artisanal industries could be developed around the treatment plants using this biomass, which could contribute to the employment market, bringing economic benefits to the end users. In addition to the advantages cited here about the interesting performances of the CWs, implementation of such green technologies in rural areas leads to the emergence of new ecosystems for biodiversity conservation and thus contributes to the attenuation of climate change effects (carbon sequestration) in arid and semi-arid areas.

1.7 Conclusions

The development of sanitation techniques adapted to rural areas in Morocco, characterized by an arid climate and a generally dispersed habitat, is an alternative to fight against pollution, preserve scarce water resources, and improve the quality of life and the well-being of the rural population. In order to contribute to solving this problem, a number of alternative technologies such as constructed wetlands (CWs) have been investigated and developed, based on small-scale treatment systems that are adapted to the needs of rural communities. Recently, full-scale CWs have been applied in some villages in Morocco using different sanitation typologies. After several years of operation, these green technologies confirmed their excellent efficiency in treating domestic wastewater characterized by high load of organic matter, nutrients, fecal coliforms and pathogens; and to adapt to the arid climate of Morocco. CWs characterized by low investment and operating costs compared to conventional systems are proved, according to the presented case studies in this chapter, to be the sustainable solution of the future for rural agglomerations, especially from an ecological and economic point of view. The advantages of CWs are based on the ease of implementation, operation and maintenance, ecological integration, and absence of power consumption. In addition, they offer a good quality of treated water, often in compliance with the Moroccan standards for direct discharge and for reuse in irrigation, mainly in rural arid areas suffering from water scarcity. Therefore, the presented case studies could be considered best practices for using such green and sustainable technology to be implemented in other rural areas in Morocco and in other developing countries. Thus, enhancing communication and elaborating guidelines providing useful information on how to implement, operate, and maintain CWs in Morocco are actually needed.

References

1. CREM (2018) Etat des lieux du secteur de l'eau au Maroc, Projet « CREM » Coopération Régionale pour une Gestion Durable des Ressources en Eau au Maghreb (GIZ/OSS/BGR), 172 p
2. Mahi M, Lamzouri K, Ouatar S, Hadraoui A, Bartali EL, Mandi L (2013) Improving sanitation Project Management for Unsewered rural communities in Morocco. Int J Comput Eng Info Technol (IJCEIT) 2(1):34–41
3. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 2020(12):1665
4. Moreira FD, Dias EHO (2020) Constructed wetlands applied in rural sanitation: a review. Environ Res 190(2020):110016
5. Elfanssi S, Ouazzani N, Latrach L, Hejjaj A, Mandi L (2018) Phytoremediation of domestic wastewater using a hybrid constructed wetland in mountainous rural area. Int J Phytoremediation 20(1):75–87
6. Dotro G, Langergraber G, Molle P, Nivala J, Puigagut J, Stein O, Von Sperling M (2017) Biological wastewater treatment series – treatment wetlands, vol 7. IWA Publishing

7. HCP (2014) Haut-Commissariat au Plan, Recensement général de la population et de l'habitat au Maroc 2014
8. Morocco country brief (2019) Sector ministers' meeting 2019, San José-Costa Rica, 4–5 April, 6 p
9. WHO-UNICEF (2017) World Health Organization, UNICEF– the United Nations Children's Fund, 2017. Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines. WHO, Geneva
10. MI (2016) Programme National d'Assainissement liquide en milieu Rural (PNAR). Direction de l'Eau et de l'Assainissement, Ministère de l'Intérieur
11. EURONET Consortium (2014) Étude d'assainissement en milieu rural au Maroc, Rapport final, version définitive, 4 avril 2014, Contrat Cadre Bénéficiaires EuropeAid/127054/C/SER/Multi6Lot6 Environnement, Demande N°2012/291 867. 133p
12. PNAR (2013) Projet de programme national d'assainissement en milieu rural, Étude d'assainissement en milieu rural au Maroc, Rapport de phase 3: formulation. Programme National d'Assainissement Liquide et d'Epuration des Eaux Usées. Septembre 2013. Royaume du MAROC. p. 17
13. CESE (2017) Développement du monde rural, défis et perspectives, Avis du Conseil Economique, Social et Environnemental, Auto-Saisine n°29/2017, 29 p
14. Mandi L, Darley J, Barbre J, Baleux B (1992) Essais d'épuration des eaux usées de Marrakech par la jacinthe d'eau (charges organique, bactérienne et parasitologique). Revue des Sciences de l'eau 5(3):313–333
15. Mandi L, Ouazzani N, Bouhoum K, Boussaid A (1993) Wastewater treatment by stabilization ponds with and without macrophytes under arid climate. Water Sci Technol 28(10):177–181
16. Mandi L (1994) Marrakech wastewater purification experiment using vascular aquatic plants (*Eichhornia crassipes* and *Lemna gibba*). Water Sci Technol 29(4):283–287
17. Mandi L, Bouhoum K, Asmama S, Schwartzbrod J (1996) Wastewater treatment by reed beds. Exp Approach Water Res 30(9):2009–2016
18. Abissy M, Mandi L (1999) Utilisation des plantes aquatiques enracinées pour le traitement des eaux usées : cas du roseau. Revue des Sciences de l'Eau 12(2):285–315
19. Abissy M, Mandi L (1999) Comparative study of wastewater purification efficiencies of two emergent helophytes: *Typha latifolia* and *Juncus subulatus* under arid climate. Wat Sci Tech 39(10–11):123–126
20. Mandi L, Bouhoum K, Ouazzani N (1998) Application of constructed wetlands for domestic wastewater treatment in an arid climate. J Water Sci Technol 38:379–387
21. El Hamouri B, Nazih J, Lahjouj J (2007) Subsurface-horizontal flow constructed wetland for sewage treatment under Moroccan climate conditions. Desalination 215:153–158
22. El Hamouri B, Kinsley C, Crolla A (2012) A hybrid wetland for small community wastewater treatment in Morocco. Sustain Sanitation Pract 12(2012):22–26
23. WHO (2006) Guidelines for the safe use of wastewater, excreta and greywater. Volume 2: wastewater use in agriculture
24. Vymazal J (2013) The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development. Water Res 47:4795–4811
25. Chen J, Liu YS, Su HC, Ying GF, Liu F, Liu SS, He LY, Chen ZF, Yang YQ, Chen FR (2015) Removal of antibiotics and antibiotic resistance genes in rural wastewater by an integrated constructed wetland. Environ Sci Pollut Res 22:1794–1803
26. Zhang DQ, Jinadasa K, Gersberg RM, Liu Y, Ng WJ, Tan SK (2014) Application of constructed wetlands for wastewater treatment in developing countries - a review of recent developments (2000–2013). J Environ Manag 141:116–131
27. Valeurs Limites Spécifiques de Rejet Domestique, Maroc. Arrêté n°1607–06 du Joumada II 1427 (25 Juillet 2006). Secrétariat d'Etat Auprès du Ministère de l'Energie, des Mines, de l'Eau et de l'Environnement, Chargé de l'Eau et de l'Environnement, Département de l'Eau. Royaume du Maroc, pp. 50

28. Normes de qualité des eaux destinées à l'irrigation, Maroc (2007) Secrétariat d'état auprès du ministère de l'énergie, des mines, de l'eau et de l'environnement, chargé de l'eau et de l'environnement
29. Kadlec RH, Wallace SD (2009) Treatment wetlands, 2nd edn. CRC Press, Boca Raton
30. Zhang D, Gersberg RM, Keat TS (2009) Review constructed wetlands in China. Ecol Eng 35:1367–1378
31. Noyes R (1994) Unit operations in environmental engineering. Noyes Publications, Park Ridge (NJ), pp 40–43
32. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380:48–65
33. Wu S, Carvalho PN, Müller JA, Manoj VR, Dong R (2016) Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators. Sci Total Environ 541:8–22
34. Moroccan Standards (2006) Moroccan standard approved by order of the minister of industry, Trade and Economy Last Level. Moroccan Industrial Standardization Service
35. Li M, Zhang H, Lemckert C, Roiko A, Stratton H (2018) On the hydrodynamics and treatment efficiency of waste stabilisation ponds: from a literature review to a strategic evaluation framework. J Clean Prod 183:495–514
36. Çakir R, Gidirislioglu A, Çebi U (2015) A study on the effects of different hydraulic loading rates (HLR) on pollutant removal efficiency of subsurface horizontal-flow constructed wetlands used for treatment of domestic wastewaters. J Environ Manag 164:121–128
37. Temel FA, Avci E, Ardali Y (2018) Full scale subsurface flow constructed wetlands for domestic wastewater treatment: 3 years' experience. Environ Prog Sustain Energy 37(4):1348–1360
38. Jozwiakowski K, Marzeca M, Alina Kowalczyk-Ju'skoa A, Gizinska-Gorna M, Pytka-Woszczyłoa A, Malika A, Listosza A, Gajewskab M (2019) 25 years of research and experiences about the application of constructed wetlands in southeastern Poland. Ecol Eng 127:440–453
39. Vera L, Martel G, Marquez M (2013) Two years monitoring of the natural system for wastewater reclamation in Santa Lucía, Gran Canaria Island. Ecol Eng 50:21–30
40. Latrach L, Ouazzani N, Hejjaj A, Mahi M, Masunaga T, Mandi L (2018) Two-stagevertical flow multi-soil-layering (MSL) technology for efficient removal of coliforms and human pathogens from domestic wastewater in rural areas under arid climate. Int J Hyg Environ Health 221:64–80
41. Lamzouri K (2018) Development and adaptation of alternative domestic wastewater purification systems. PhD. Dissertation, Agronomic and Veterinary Institute Hassan II, Rabat, Morocco. 270p
42. Chen X, Luo AC, Sato K, Wakatsuki T, Masunaga T (2009) An introduction of a multi-soil-layering system: a novel green technology for wastewater treatment in rural areas. Water Environ 23:255–262
43. Song P, Huang G, An C, Shen J, Zhang P, Chen X, Sun C (2018) Treatment of rural domestic wastewater using multi-soil-layering systems: performance evaluation, factorial analysis and numerical modeling. Sci Total Environ 644:536–546
44. Zhang TX, Inoue M, Kato K, Izumoto H, Harada J, Wu D, Sakuragi H, Ietsugu H, Sugawara Y (2017) Multi-stage hybrid subsurface flow constructed wetlands for treating piggery and dairy wastewater in cold climate. Environ Technol 38(2):183–191
45. Sato K, Masunaga T, Wakatsuki T (2005) Characterization of treatment processes and mechanisms of COD, phosphorus and nitrogen removal in a multi-soil-layering system. Soil Sci Plant Nutr 51:213–221
46. Stevik TK, Aa K, Ausland G, Hanssen JF (2004) Retention and removal of pathogenic bacteria in wastewater percolating through porous media: a review. Water Res 38:1355–1367
47. Latrach L, Ouazzani N, Masunaga T, Hejjaj A, Bouhoum K, Mahi M, Mandi L (2016) Domestic wastewater disinfection by combined treatment using multi-soil-layerin system and sand filters (MSL-SF): a laboratory pilot study. Ecol Eng 91:294–301

48. Lutterbeck CA, Kist LT, Zerwes FV, Lopez DR, Machado EL (2017) Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas. J Clean Prod 148:527–536
49. Gao J, Chen S, Wang W, Yan Q, Jiang N, Ruiqin Z (2012) Effects of unpowered complex eco-technology on sewage purification in central Chinese rural areas. Pol J Environ Stud 21(6):1595–1602
50. Kouki S, M'hiri F, Saidi N, Belaïd S, Hassen A (2009) Performances of a constructed wetland treating domestic wastewaters during a macrophytes life cycle. Desalination 246:452–467
51. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360. S0925857421002159 106360. https://doi.org/10.1016/j.ecoleng.2021.106360
52. Gaballah MS, Abdelwahab O, Barakat KM, Stefanakis AI (2022) A pilot system integrating a settling technique and a horizontal subsurface flow constructed wetland for the treatment of polluted lake water. Chemosphere 295:133844. S004565352200337X 133844. https://doi.org/10.1016/j.chemosphere.2022.133844

Chapter 2
Efficiency of Constructed Wetlands and Wastewater Stabilization Ponds for Wastewater Treatment in Northern Algerian Sahara

Khaled Bouchama

Abstract Algeria is facing for years a real problem of water supply. The burgeoning population, coupled with pollution and inadequate governance arrangements, are leading to the depletion of water resources, and the crisis may worsen in the coming years if nothing is done. To extend the treatment of wastewater by natural systems, several experimental pilots and full-scale wastewater treatment systems have been tested in northern Algerian Sahara such as in Brézina, Temacine and Kef el Doukhan regions. Brézina constructed wetland (CW) is a Hybrid system with horizontal subsurface flow (HSSFCW) and free water surface flow (FWSCW) beds. Temacine CW is an HSSFCW planted with 23 different plant species and macrophytes. The lagoon system of Kef el Doukhan is a wastewater stabilization pond (WSP) designed to treat the wastewater in three phases (preliminary, primary and secondary treatment). The physicochemical analyses of wastewater at the three systems's outflows revealed that the planted HSSFCW of Temacine was more efficient than the hybrid (HSSF and FWS) CW of Brezina and Kef el Doukhan WSP. Overall, the removal efficiency of TSS, COD, BOD_5, $P\text{-}PO_4^{3-}$, $N\text{-}NO_2$ and $N\text{-}NO_3$ were higher in Temacine CW. However, relatively low effectiveness for electrical conductivity (EC) removal was observed; EC increased by almost 39% essentially due to the long dry season, high rate of evaporation and naturally high levels of dissolved salts in water. Despite an encouraging efficiency in removing organic contamination (COD, BOD_5), TSS, EC, and reducing the total amount of nitrogen and phosphate in the effluents, the values of the physicochemical parameters at the outlet of Brezina CW and Kef el Doukhan WSP exceeded Algerian standards for reuse in irrigation and environmental discharges. To improve their removal efficiency, it is reasonable to provide a tertiary treatment using maturation ponds in Kef el Doukhan WSP and review the design of Brezina CW.

K. Bouchama (✉)
Ecology and environment department, Khenchela University, Khenchela, Algeria

Biology Department, Faculty of Sciences, Badji Mokhtar Annaba University, Annaba, Algeria
e-mail: bouchama.khaled@univ-khenchela.dz; khaled.bouchama@yahoo.fr

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_2

Keywords Algerian Sahara · Arid climate · Constructed wetland · Natural lagoon · Oasis

2.1 Introduction

In North Africa countries, Algeria is the most vulnerable to climate change and water stress, mainly due to its high sensitivity. The combination of climate change and strong population growth is likely to further aggravate the already scarce water situation [1]. In Algeria, the water resources are estimated at 19 billion m^3/year [2, 3], providing an approximate annual volume of 600 m^3/inhabitant/year [4]. These figures place Algeria in the category of countries poor in water resources, under the shortage threshold set by the UNDP (United Nations Development Programme) or the scarcity set by the World Bank of 1000 m^3/inhabitant/year [5]. Several factors can explain the water stress situation in Algeria:

- The decrease in rainfall; the mean annual precipitation is 200–400 mm overall [6]. In the Sahara and south the of Saharan atlas, the annual amount of rain is below 100 mm [2].
- Increasing demand for water due to demographic growth multiplied by four in 40 years. Algeria's demography increased to 43.9 million inhabitants in January 2020; it was 41.3 million in 2017 [7].
- The majority of dams lost part of their capacities because of material deposits and lack of maintenance [8].
- The untreated domestic and industrial effluents pollute surface and underground resources, while increased salinity was reported in several cases resulting from exhaustive underground water exploitation [8–10].
- The use of non-conventional water resources such as treated wastewater and desalinization is not common [2].
- Algeria has an area of almost 2.4 million square kilometres, more than four-fifths of which is desert [6]. With its arid and semi-arid climate, Algeria is highly vulnerable to climate change with desertification as a major concern. Overall, temperature and evaporative demand are expected to increase [11].

To equilibrate the water balance, Algeria is committed to the mobilization and development of non-conventional water resources such as desalination and wastewater reuse as a strategic component of future water policy [12]. In the last decades, systems have been constructed copying natural processes for water quality improvement and water purification such as phytoremediation and constructed wetlands (CWs) [13, 14].

In countries with hot and dry climates, different types of CWs have been applied to treat domestic, municipal, industrial and agro-industrial wastewater [15]. Pilot-scale and/or full scale constructed wetlands have been tested and constructed in several countries with hot and dry climates; Algeria [16, 17], Morocco [18–20], Tunisia [19, 21], Egypt [19, 22, 23], Palestine [24], Jordan [25], Iran [26, 27, 28], Oman [15, 29, 60], USA (Nevada) [30] and Australia [31].

Natural lagoon systems, also called wastewater stabilization ponds (WSPs) have been applied in several countries like Algeria [32, 33], Niger [34], Morocco [35, 36], Palestine [37], and Egypt [38]. WSPs are often made up of several watertight basins or microphyte lagoons, operating in series to treat wastewater for a predetermined period [39]. The treated wastewater by these systems in arid and semi-arid climates is particularly valuable for irrigation where natural waters are insufficient, and nutrient depleted [40].

For several years, Algeria and in particular the south has suffered from a real problem of water shortage, mainly due to the water salinity in the Saharan areas and water table pollution by infiltration of wastewater discharges. In addition, the rise in the water table directly linked to the release of urban wastewater causes a gradual degradation of the palm oases. To expand wastewater treatment by natural systems and reuse treated water for irrigation, different wastewater treatment systems have been tested at pilot or full scale to reproduce the appropriate design to the Sahara climatic conditions.

This chapter provides an overview of the efficiency of Brézina and Temacine CWs, and Kef el Doukhan WSP in treating wastewater, focusing on the main factors hindering the use of this technique in North Algerian Sahara.

2.2 Brézina Constructed Wetland

With the aim of extending the wastewater treatment by natural systems and produce better quality wastewater through phytoremediation systems, an integrated, sustainable model for oasis protection, recovery, and development has been realized in Brézina oasis [41].

The Oasis of Brézina (33°5′38” N – 1°15′3.40″ E) is located in the pre-Saharan region (800 m a.s.l.) south of the wilaya (department) of El Bayadh, 700 km south of Algiers, Algeria [17, 41]. In Brézina oasis, the climate is arid; monthly average temperatures range from a minimum of 9 °C in January to a maximum of 35 °C in August [41]. Precipitation is less than 100 mm per year, with a relative humidity of 40%. Average solar radiation is 4.6 kWh/m^2, and the wind speed can reach 5.9 m/s during the sandstorms of April month [42].

The main problems that afflict Brézina oasis are the groundwater depletion resulting from an increasing urban population, and the risk of groundwater contamination due to the discharge of untreated wastewater. All these cause severe damages to the palm grove [17].

2.2.1 Design of Brézina Constructed Wetland

The main goal of Brézina CW was to face the challenge from two different perspectives; the first concern is adopting a new water management model inspired by collecting, recycling and reusing urban wastewater. The second proposes a new

Fig. 2.1 View of the Constructed wetlands of Brézina Oasis under construction [42]

Fig. 2.2 Constructed wetlands of Brézina Oasis (October-2013) [17]

agroforestry strategy to stimulate alternative economic chains and environmental restoration [17]. The CW has a treatment capacity of 30 m^3/day, with two parallel natural treatment chains (constructed wetlands B and A) (Figs. 2.1 and 2.2). The CW of Brézina is a Hybrid system: horizontal subsurface flow (HSSFCW) and Free water surface flow (FWSCW) [17, 42]. The waterproofing of the cells or the basins is ensured by a compacted layer of clay of at least 20 cm and a geomembrane covering in high-density polyethylene (1.5 mm). The design and dimensions of Brézina CW are shown in Table 2.1 [16].

Section (B) is a constructed wetland with a free surface flow system composed of three cells alternating aerobic (cell 1 and cell 3) to anaerobic process in cell 2 (Fig. 2.3). Cell 1 is designed to provide preliminary sedimentation with a water level up to 30 cm, and the vegetation is emergent with a density of 90%. Cell 2 is

Table 2.1 Design and dimensions of Brézina constructed wetland [16, 17]

Constructed wetland	Treatment Basin	Dimension		Treatment capacity (m^3/day)	Type of constructed wetland
		Length x width (m)	Depth (m)		
Section (A)	Cell 1 and cell 3	20 x 10	0.7–1	20	Horizontal subsurface flow (HSSFCW)
	Cell 2	12 x 10	0.7–0.9		
Section (B)	Cell 1 and cell 3	19 x 9	0.5	10	Free water surface (FWSCW)
	Cell 2	12 x 9	0.8		
Water storage	Water storage treatment reservoir (WSTR)	24 x 11	2	–	–

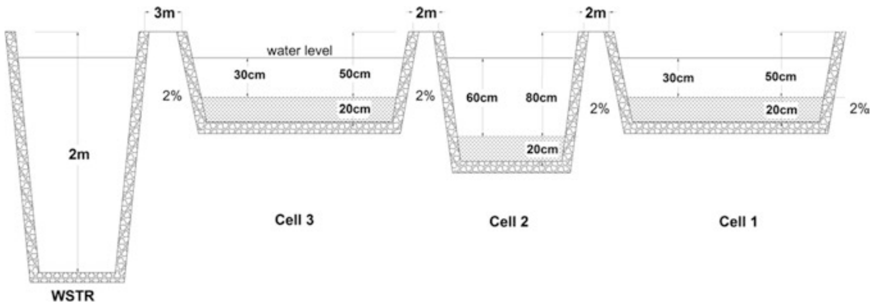


Fig. 2.3 Constructed wetland section (**b**) with free surface flow [17]

designed to provide anaerobic digestion of Cell 1 effluent, water level never exceeds 60 cm, and the vegetation is submerged with a density of 20%. Cell 3 is designed to complete the water treatment of Cell 2 effluent through an aerobic process. The water level is up to 30 cm, and vegetation is emergent with a density of 90% (Fig. 2.1) [17].

The CW (**a**) is of horizontal subsurface flow comprising three separated cells where mainly aerobic processes are triggered (Fig. 2.4) [17].

The water level should never exceed 30 cm in the aerobic cells (cell 1 and cell 3) and 60 cm in the anaerobic cell (cell 2) to increase the efficiency of the constructed wetland and the growth of the selected plant species [17, 42]. Two different mixes of plant species were chosen; the first mix of plants was composed of *Phalaris arundinacea L., Juncus spp., Phragmites spp., and Typha spp.* optimal for reduced water depth and resistance to short periods of dryness. The second mix (*Myriophyllum spp., Typha spp.*) is optimal to favour anaerobic processes [17]. The treated wastewater will be used to produce wood biomass for local consumption (*e.g., Tamarix)* and to produce forage, wood and non-wood products (e.g., *Argania spinosa L., Pistacia* atlantica *Desf., Olea europaea L., Populus spp.).*

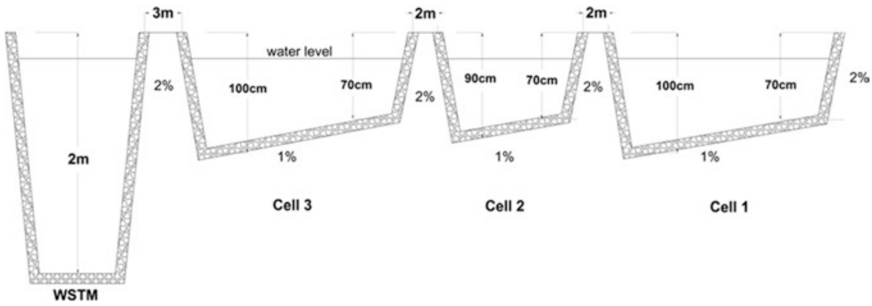


Fig. 2.4 Constructed wetland section (**a**) with Horizontal subsurface flow [17]

Table 2.2 Characteristics of wastewater at the inflow and outflow of Brézina constructed wetland

Parameters	Wastewater [42]	Treated wastewater [42]	Treated wastewater [16]	Algerian standard	
				Discharge [44]	Irrigation [45]
T [°C]	–	–	–	< 30	–
EC [ds/cm]	–	–	–	–	3
pH	–	–	–	6.5–8.5	6.5–8.5
TSS [mg/L]	417	35	82% removed	35	30
BOD_5 [mg/L]	161	25	67% removed	35	30
COD [mg/L]	No measured	125	≤ 120 mg/l	120	90
Total phosphorus [mg/L]	0.947	15	80% removed	10	–
Total nitrogen [mg/L]	49	30	36% removed	30	30
TC [CFU/100 mL]	10^5	10^3	95% removed	–	< 100
Nematode eggs [egg/100 mL]	1	1	No measured	–	0 to <1

2.2.2 Efficiency of Brézina Constructed Wetland

According to the study of Benslimane et al. [16] (Table 2.2), the physico-chemical analysis of wastewater at the inlet and outlet of the pilot included: Total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), total nitrogen (TN), total phosphorus (TP) and total coliforms (TC). Results showed an acceptable treatment performance. The average removal efficiency of TSS and BOD_5 was 82% and 67%, respectively. The content of TP decreased by almost 80%. This trend is also observed for COD and TC. The study concluded that the general performance of the treatment system is within the permissible limits of Algerian standards for reuse in irrigation. However, relatively low effectiveness for TN removal has been recorded. Transformation and removal of nitrogen in CWs are mainly accomplished by ammonification, nitrification and denitrification as well as plant uptake, that are influenced by the temperature and hydraulic residence time [43]. Moderate performance for TN removal in this case study could be due to a weaker denitrification rate.

The denitrification process requires anaerobic or low-oxygen conditions and can only occur in the CW's anoxic zones. In Brezina CW, only one of the six basins was designed for anaerobic conditions; this likely affected nitrogen removal efficiency by reducing the hydraulic residence time required for denitrification. A single basin with the selected dimensions (Table 2.1) cannot achieve high nitrogen removal efficiency. The increased volume of cell 2 and the hydraulic residence time could improve nitrogen removal. In addition, a lack of carbon source in the wastewater also affects the denitrification process in HSSFCWs [46, 60]. However, introducing an external carbon source may reduce dissolved oxygen (DO) levels, which is beneficial for successful denitrification [47, 60].

The results of Benslimane et al. [16] study was in accordance with those of De Angelis et al. [42] (Table 2.1). The removal efficiency of TN was 38%, with an average of 30 mg/L in the outlet. The removal efficiency of TSS, BOD_5, and TC was 91%, 84, and 99%, respectively. Only two indicators, COD (125 mg/L) and TP (15 mg/L) in the treated effluent were above the country's permissible limit for reuse in agricultural irrigation and discharge into the environment. According to De Angelis et al. [42], total phosphorus concentration increased by more than 15 times in the outlet of the system. In CWs, the major phosphorus removal processes are sorption, precipitation, plant uptake (with subsequent harvest) and peat/soil accretion. However, the first three processes are saturable and soil accretion occurs only in FWS CWs [48]. Increased TP concentration in Brézina CW was probably due to the imbalance between phosphorus released in wastewater by phosphate solubilizing microorganisms and the quantity removed by macrophytes and the polyphosphate accumulating organisms (PAOs), which are mainly responsible for phosphorus removal.

In addition, excess fertilization and manure use in the oasis of Brézina could cause a phosphorus surplus to accumulate in the soil, some of which is transported by runoff to the basins. Effectively in the first year of operation, the basins of CW were partially damaged by flooding events [41]. Brézina CW was designed without walls to protect the basins against flooding and sandstorm. Wind erosion by sirocco (a frequent wind in the region) could fill the basins with sand and soil, which certainly affecting the global removal efficiency if a maintenance operation was not carried out. The release of phosphorus from the sediments into the water column is another possible explanation for the increase in TP content. As reported by Araújo et al. [49] the cyclic transformations of phosphorus occur in both the water column and sediments and involve both physicochemical and biological processes. Phosphorus is removed mainly by the sedimentation of particulate organic material and chemical precipitation and the formation of sediments. However, many factors such as redox conditions, pH levels and mixing, for instance, may favour phosphorus release from sediments back to the water column.

2.3 Temacine Constructed Wetland

The CW is located near a small town called Temacine (33° 01’ N and 06° 00′E), 10 km south of Touggourt city, Ouargla (681 km south-east from the capital Algiers), an area with a high environmental and archaeological value. The wastewater treatment plant collects domestic and urban wastewaters from the small and old village called ‘Ksar Temacine’ [50, 51]. Temacine is characterized by a hot desert climate, dry during summer and cold from December to February. Temperatures are generally high (45–50 °C) in the hottest months (June to August). Rainfall in the region is negligible and irregular throughout the seasons and years. In 2009, the maximum rainfall was recorded during the month of March with only 19 mm. Evaporation is very high, with its intensity being strongly reinforced by hot winds; the maximum value recorded in the region in 2019 was 420 mm in June [52].

2.3.1 Design of Temacine Constructed Wetland

The CW is of horizontal subsurface flow, sized to treat 15–22 m^3/day of urban wastewater, corresponding to the production of 100–150 people or 20 houses at a rate of 150 L/per/day [51, 53]. Two successive stages comprise the wastewater treatment system; primary treatment (physical) is provided with a septic system, consisting of three cells with a volume of 45 m^3, and 3 days residence time of wastewater in the pit (Table 2.3). At the outflow, the water is filtered through a filter of palm fiber (lif) [51]. There is a growing interest in using palm fiber (lif) to absorb organics and nutrients (P, N...) in wastewater. Date-palm fiber filter has excellent potential for tertiary domestic wastewater treatment; it is reported to remove up to 54.9% of turbidity, 57.7% of total phosphorus and 98% of helminth eggs [54].

The secondary biological treatment is built in a 400 m^3 tank (crescent-shape geometry). The tank was filled with 70 cm of gravel, and the wastewater level is kept 10–15 cm below the gravel. Subsurface flow means that the wastewater is not in contact with the air; this has the advantage of avoiding any human contact, odors, or the proliferation of mosquitoes. Inside the basin, walls allow water to stay

Table 2.3 Design and dimensions of Temacine constructed wetland [50, 51, 55].

Constructed wetland	Treatment Basin	Substrate media	Dimension		Residence time (day)	Treatment capacity (m^3/day)
			Volume (m^3)	Depth (m)		
Primary physical treatment (septic tank)	03 cells	Palm fiber (lif)	45	0,8	3	15–22
Secondary biological treatment (HSSFCW)	01 tank	Gravel	400	1	4	

Fig. 2.5 Early construction phase of the constructed wetland at Témacine [55]

for 4 days, which means a total residence time of 7 days [53, 54]. In the constructed wetland, 23 different plant species recognized by their ability to tolerate the local climate were planted, such as *Juncus maritimus, Cyperus papyrus, Canna indica, Typha angustifolia, Nerium oleander, Washingtonia filifera, Vétivéria zizanioides, Mentha Spicata, Ficus Carica, Jasminum Grandiflorum, Hibiscus Rosa-sinensis, and Lantana Camara.* The water discharged from the basin is directed to drainage trenches that feed a green zone planted by fruit trees [51, 55] (Fig. 2.5).

2.3.2 Efficiency of Temacine CW

The performance of the Temacine CW for wastewater treatment was examined. Physical and chemical parameters of wastewater were analyzed at the inflow and outflow of the pilot: Temperature (°C), pH, conductivity (EC), Total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), dissolved oxygen concentrations (DO), nitrate nitrogen $N\text{-}NO_2^-$, nitrite nitrogen ($N\text{-}NO_3^-$), orthophosphate ($P\text{-}PO_4^{3-}$) and total coliforms (TC) (Table 2.4). Several studies evaluated the effectiveness of the Temacine CW pilot [50, 53, 56].

The results of studies conducted by Hammadi et al. [52], Bachi et al. [50], and Tidjani [56] on Temacine CW, revealed a similar removal efficiency (Table 2.4). In the three studies, total coliforms removal was up to 90%, the removal efficiency of TSS ranged from 70%–90%, COD from 80% - 91%, BOD5 from 75% - 96% and $P\text{-}PO_4^{3-}$ removals ranged from 51% to 98%. Regarding nitrogen removal efficiency, the nitrate reduction rate ranged from 94 to 99% [50, 56]. The high removal rate of $N\text{-}NO_3^-$ could be due to a good condition for denitrification and/or the uptake of nitrate by macrophytes (*Juncus maritimus, Cyperus papyrus, Canna indica, Typha angustifolia*) and other plant species *(Nerium oleander, Washingtonia filifera)*. With 70 cm of gravel as substrate media in the secondary biological treatment tank, the

Table 2.4 Characteristics of wastewater at the inflow and outflow of the Temacine constructed wetland. (The results represent the maximum and minimum values of each parameter, the number with an asterisk (*) represents the average)

Parameters	Wastewater characteristics [53]		Wastewater characteristics [50]		Wastewater characteristics [56]	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
pH (−)	7.6–8.48	6.6–7.2	7.09–7.38	6–8	7.2–7.91	6.63–7.46
T (°C)	–	–	18.6–33.4	≥ 29.7	18.2–29.5	15.7–29.1
EC [mS/cm]	4.58–5.95	5.38–6.07	–	–	2.95–3.36	3.03–5.48
TSS [mg/L]	125–813	20–75	117–296	< 35	62.9–529.5	4–30
COD [mg/L]	179.5–530	35–98.30	260–380	< 120	110–528.5	19.4–39.5
BOD5 [mg/L]	–	–	140–300	< 35	80.4–292.5	3–25.5
DO [mg/L]	0.10–0.25	0.21–1.60	–	–	–	–
N-NO_2 [mg/L]	–	–	0.02–0.13	1.8*	0.02–0.06	0.001–0.028
N-NO^3 [mg/L]	–	–	15.4–30	0.01*	12.2–55	0.8–6.7
P-PO_4^3 [mg/L]	20.2–34.3	8.60–17.90	6–18	3*	2.23–20.3	0.13–0.44
TC [CFU/100 mL]	1500000*	Removal of 90%	–	–	450000*	6*

anaerobic conditions at the bottom of the CW were probably optimum for the denitrification process. In addition, dissolved oxygen concentrations at the inlet of the CW was between 0.10–0.25 mg/L, which seemed favorable for an efficient denitrification. Similar results were found by Cui et al. [57]; a good denitrification efficiency was observed when DO concentrations in the HSSFCW were between 0.5–4.5 mg/l. The temperature in Temacine region seems positively affecting the nitrate and TP removal efficiency; at the outlet, the treated water temperature can reach 29.7 °C. According to Zhou et al. [58], temperature could substantially influence the performance of CWs, since the removal percentages of $NH4^+$, NO_3^-, TN, and TP in CW tended to decrease with temperature decline. Concerning the high orthophosphates removal (P-PO_4^{3-}) in Temacine CW, this could be explained by the direct uptake of P-PO_4^{3-} by plants or attributed to adsorption on the substrate medium (gravel). In addition, microbial populations residing in submerged roots can also assimilate orthophosphates.

The effectiveness of the Temacine CW on salinity levels was estimated indirectly through electrical conductivity (EC). The results showed an increase in EC at the outlet of 2% [52] and 39% [56] for different seasons. Several studies in hot regions and under simulated hot arid climatic conditions have reported an increase in salinity at the outlet of constructed wetlands [59–61]. Wastewater usually has a higher electrical conductivity, especially in regions with hot climates due to the long dry season and the high rate of evaporation [62]. According to Bettahar et al. [63], in the Algerian Sahara, the mineralization and salinity of the water are generally of geological origin. In hot and drylands, salinity is enhanced by intense solar radiation, increased evapotranspiration and poses additional challenges for decentralized water-treatment systems such as CWs [61]. Within arid and hot areas, CWs functions may be altered compared to temperate and humid climates, evaporation and plant transpiration, altering the water balance in these systems and increasing salinity values [15].

To reduce water salinity in the outflow of the Temacine CW, particular attention must be paid to selecting plants with high water use efficiency to reduce evapotranspiration losses. Testing one or a mixture of these species (*Arundo donax, Phragmites australis, Typha latifolia* and *Sarcocornia fruticosa*) could improve salt removal efficiency from the system. According to Wagner et al. [59], *Typha latifolia* and *Phragmites australis* can tolerate high salinity and a temperature of 30 °C, demonstrating that these plant species are suitable choices for wastewater treatment of salty water in a hot and arid climate. Proportions of plant species in CWs could also affect the system effectiveness. In Temacine CW, the increase in the proportion of *Canna indica* species could lead to a decrease in salinity at the outlet. According to the study of Liang et al. [64], *Canna indica* showed good removal efficiency of nutrients (N, P) and salinity in a CW mesocosm under greenhouse conditions. In addition, it is essential to choose the adequate residence time of wastewater in the W. Evapotranspiration losses can be significant in arid climates, especially if relatively long residence times are required for the treatment.

2.4 Kef el Doukhan Wastewater Stabilization Pond

The Mzab region is located 600 km south of the capital city of Algeria. Agriculture is the main activity based on an oasis agriculture system: date palm (45%), vegetable crops (14%) and fruit trees (12%) [65]. In the region, floods and groundwater pollution are the inhabitants' main concerns. For several years, the water table was polluted by infiltration water from irrigation and wastewater discharges. In addition, under the combined effect of the decrease in water withdrawals and the increase in recharge, this water table tended to rise in low-lying areas such as palm groves, leading to the degradation of crops and date palm in the oases [66–68]. Therefore, the Algerian authorities have decided to create a natural lagoon treatment; the Mzab wastewater treatment plant is part of a program to preserve the environment and water resources in the region.

The lagoon system is located in El Atteuf (kef el Doukhan) at the downstream of the valley of Mzab [69]. A hot and dry desert climate characterizes the region; rainfall ranges from 70 to 30 mm/year and the temperatures can exceed 45 °C in the summer period. The air's relative humidity is very low and the winds are relatively frequent (sirocco) [70]. Evaporation varies between 2.5 m in the northern regions and more than 3.5 m south of Mzab valley [66].

2.4.1 Design of Kef el Doukhan Wastewater Stabilization Pond

The WSP of Kef el Doukhan is designed to treat domestic wastewater by natural lagoon system to produce an effluent quality that complies with the WHO's and Algerian discharge standards and reuse the treated water for irrigation [66]. The natural lagoon system was built on a surface area of 79 hectares (790,000 m^2) and was designed to treat the wastewater in three phases (preliminary, primary and secondary treatment) and to dewater sludge in the drying beds [33]. (Fig. 2.6).

The system comprises 16 basins divided into 2 levels and 10 beds of drying, with a maximum treatment capacity of 46,700 m^3/day corresponding to 331,700 persons equivalent. Design and dimensions of Kef el Doukhan WSP are summarized in Table 2.5.

Fig. 2.6 Aerial view of the Kef el Doukhan natural lagoon systems [66]

Table 2.5 Design and dimensions of the Kef el Doukhan WSP

			Dimension			
Constructed wetland	Treatment Basin	Waterproofing and Substrate media	Volume (m^3)	Depth (m)	Residence time (day)	Treatment capacity (m^3/day)
Primary treatment	8 anaerobic lagoons	Elastomeric bitumen geomembrane without media	174,029 (8 lagoons)	3.5	3	46,700
Secondary treatment	08 aerobic lagoons		46,000 (8 lagoons)	1.6	10	
Drying beds	10	Washed sand	–	–	–	–

Table 2.6 Characteristics of wastewater at the inflow and the outflow of Ghardaïa WSP (the results represent the average, the number with an asterisk (*) represents maximum and minimum values of each parameter)

	Wastewater characteristics [71]		Wastewater characteristics [66]		Wastewater characteristics [72]	
Parameters	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
pH (–)	7.73–8.47*	8.02–8.44*	7.6	8.1	7.84	8.48
T (°C)	–	–	21.2	20.2	19	18.5
EC [mS/m]	3.37–3.68*	2.68–3.19*	3.82	3.17	3.69	3.11
TSS [mg/L]	92.66	86.08	143.1	55.7	70	91
COD [mg/L]	215.25	80.85	395.0	152.5	203	137
BOD_5 [mg/L]	141.83	53.88	189.4	53.5	161	94
NH4+ [mg/L]	–	–	30.7	31.7	19.08	32.18
N-NO_{2-} [mg/L]	–	–	0.5	0.45	–	–
N-NO^3 [mg/L]	–	–	1.4	0.6	–	–
P-PO_4^3 [mg/L]	–	–	3.6	3.0	–	–

2.4.2 *Efficiency of Kef el Doukhan Wastewater Treatment Pond*

The main objective of the Kef el Doukhan WSP was to protect the receiving environment, surface and underground water resources, minimize the upwelling and pollution of the water table, and reuse the treated wastewater for agricultural purposes. According to the results (Table 2.6), the purification process was ineffective. A low removal performance for most of the evaluated parameters was recorded. The effluent of Kef el Doukhan WSPs did not meet the Algerian standards for reuse in irrigation and discharge into the environment (Table 2.6).

Overall, the alkalinity of the wastewater in Kef el Doukhan WSP has increased. Despite this, the pH of the effluent is within Algeria's standards for irrigation and discharge to the environment ($6.5 < pH < 8.5$). In the study of Zegait and Remini [66], the average pH was 7.6 in the influent and 8.1 in the effluent. Djaani and Amer [72] obtained comparable results, with pH = 7.84 in the influent and 8.48 in the effluent. These results were similar to that reported by Mansouri et al. [73] in a WSP installed at a semi-arid region (pH ranged from 7.8 to 7.9 at the influent and from 7.9 to 8.3 at the effluent). The results are also comparable to the findings of Achag et al. [36] where the WSP is located in a desert climate city in southern Morocco (pH ranged from 7.42 to 7.9 at the influent and from 7.87 to 8.6 at the effluent).

The high photosynthetic activity of microalgae probably caused the increase in alkalinity of wastewater in Kef el Doukhan ponds. That consumes carbon dioxide faster than it can be replaced by the respiration activity of bacteria. The processes of photosynthesis and respiration of algae have a considerable influence on CO_2

availability in WSPs and, consequently, on the pH of the wastewater. According to Mara, Pearson [74], at peak algal activity, carbonate and bicarbonate ions react to provide more carbon dioxide for the algae, so leaving an excess of hydroxyl ions with the result that the pH can rise. In addition, the domination of high temperature and sunlight in Kef el Doukhan area could increased algae rate of growth. The rate of algae photosynthesis and the cellular metabolism of microorganisms in the ponds are enhanced by high temperatures and retarded by low temperatures [75]. Water's EC may be used to determine the amount of salts dissolved in it. The EC of the effluent at Kef el Doukhan WSP was slightly lower than in the influent (Table 2.6). Despite this reduction, it does not satisfy the Algerian standards requirement, which should be less than 3 ds/cm. The low efficiency of reducing the EC in the effluent is probably due to the long dry season and high evaporation rate in Ghardaïa and Mzab region. According to Boutelhig et al. [76], the Mzab valley is characterized by solar potential, which reaches about 6 kWh/m^2, within an annual sunshine duration of more than 3000 hours/year. The evaporation ranges from 2.5 m in the north to more than 3.5 m south of Mzab valley [66]. In areas with hot climates, the low performance and the ineffectiveness of WSPs in reducing the EC of the effluent was observed [36, 77]. According to Achag et al. [36], bacterial decomposition of organic matter produces nutritional salts like nitrogen and phosphate, which may increase EC in the effluent.

Concerning the removal efficiency of TSS in Kef el Doukhan WSP, the average removal ranged from 8% to 61% [71]. On the contrary, Djaani and Amer [72] recorded an increase of 23% (Table 2.6). These differences in efficiency are due to several factors like climatic conditions (temperature, wind and rainfall), composition and quantity of mineral and organic matter in the influents and the presence or no of microalgae in ponds. The average values recorded at the effluent were 86.08 mg/L [71], 55.7 mg/L [66] and 91 mg/L [72]; those values are above the Algerian standards for irrigation reuse and environmental discharge, which are 30 and 35 mg/L, respectively. Inorganic materials, sand, clay, silt, organic particles, algae, and bacteria constitute most TSS in WSPs. According to [66, 71, 72], the presence of algae in the colloidal suspension contributes to the high values of TSS in effluents. Several studies conducted in a hot climate have linked the ineffectiveness in eliminating TSS to the high growth rate of microalgae in ponds [36, 73, 78, 79]. This inefficiency could also be caused by sand and dust particles that fall into Kef el Doukhan WSP, that may be transported by winds, dust storms, and sandstorms. According to Wang [80], sand and dust storms are common weather phenomena in Algerian arid and semi-arid regions. The ineffectiveness of reducing COD and BOD_5 was also observed in Kef El Doukhan WSP. The values of these two parameters were higher than the limits set by Algerian standards for irrigation reuse (COD <90 and BOD_5 < 30 mg/L) and environmental discharge (COD <120 and BOD_5 < 35 mg/L), except of what was recorded by Benhedid et al. [71] where the COD was 80.85 mg/L. The removal rates of COD and BOD_5 were between 32% - 62% and 42% - 71%, respectively. This reduction is mainly due to solids settling, anaerobic digestion process, aerobic oxidation of organic compounds and algae presence in ponds. Several WSPs installed in hot climate countries yielded similar results: in Iran: BOD_5 (66% - 83%) and COD (59% - 76%) [73]. In Morocco: the average removal was for BOD_5 (65.4%) and COD (47%) [36]. In Tanzania: BOD_5 and COD removal was 45.3% and 62.7%, respectively [81]. In Egypt: removals were for BOD_5 (50.65%) and COD (48.95%) [82].

Inadequate hydraulic retention time (HRT) and insufficient maintenance probably reduced the COD and BOD_5 removal efficiency of Kef El Doukhan WSP. In addition, microalgae die-off in ponds could increase BOD levels as they decompose at the bottom. The primary function of anaerobic ponds is BOD removal; a properly designed and not significantly underloaded anaerobic pond will achieve around 40% BOD removal at 10 °C and over 60% at 20 °C. For wastewater with a BOD of 300 mg/L, for example 1.5 days is sufficient at a temperature of 15 °C [74]. In addition, the increase in HRT more than the recommended value may lead to the death of some bacteria and then a decrease in ponds removal efficiency [82]. The efficiency of WSPs in the removal of BOD, COD, TSS can be improved through the addition of baffles to optimise the HRT and improve plug flow conditions of the ponds [83].

Overall, the nutrient removal performance of Kef El Doukhan WSP was unsatisfactory. The total nitrogen rate in the effluent exceeded the Algerian standard limit of 30 mg/L. The ineffectiveness of Kef Doukhan WSP for ammonium removal was most likely due low nitrification and a slowdown in the transformation process. The die-off of microalgae and phytoplankton populations in the aerobic ponds resulted in a decrease in dissolved oxygen. Nitrification is an aerobic microbial nitrogen transformation process by which ammonium (NH_4^+) is converted to nitrate (NO_3^-) in two phases: oxidation of ammonium to nitrite and oxidation of nitrite to nitrate. Marek et al. [84] reported that the bacteria involved in the transformation of ammonium nitrogen need a sufficiently long time to grow. The growth rate of these organisms is primarily affected by the concentration of ammonium nitrogen and dissolved oxygen, temperature, the pH in the environment and the BOD/TN ratio.

In addition, the transformation of organic nitrogen to ammonia proceeds typically faster under sufficient oxygen concentrations. It is usually faster than nitrification, and if the latter is affected, ammonia accumulation occurs. This happens mostly during a rapid change from aerobic to anaerobic conditions. For ammonification, optimum temperature and pH range from 40 to 60 °C and 6.5 to 8.5, respectively [60, 85]. Concerning, nitrification and denitrification, the populations of nitrifying bacteria are apparently very low in WSPs, possibly due to the absence of physical attachment sites in the aerobic zone, although inhibition by the pond algae may also occur [75]. In wastewater, ammonium (NH_4^+) and unionised ammonia (NH_3) are interchangeable depending on the pH and temperature [86, 87]. At 25 °C, and pH $<$ 9.25 the dominant form is NH_4^+, while at pH $>$ 9.25 the dominant form is NH_3. At Kef el Doukahan WSP, the pH in the influents and the effluent were less than $<$9.25. This probably explains the increase in NH_4^+ in the effluent (Table 2.6). The average removal efficiency of N-NO_2^-, N-NO_3 and P-PO_4^3 in Kef el Doukhan WSP was 10%, 57% and 17%, respectively. The poor and moderate removal performance of N-NO_2^- and N-NO_3 could be due also to their low quantities in the influent. Mkude and Saria [77] observed similar results the removal effectiveness was

2.7% with 3.32 mg/L of NO_3-N in the influent. The reduction rate of NO_3-N was 52% with 0.91 mg/L in the influent [81].

The removal rate of (PO_4^{3}-P) in Kef el Doukan WSP was 17% with 3 mg/L in the final effluent, which is the maximum value authorized by Algerian standards for irrigation reuse and environmental discharge. In similar climate conditions of the WSP, Machibya and Mwanuzi [81] observed a higher removal performance of orthophosphate (29%). Furthermore, Mahassen et al. [82] found that the removal rates of dissolved phosphate and total phosphate (TP) were 51.4% and 47.8%, respectively. The efficiency of total phosphorus removal in WSP depends on how much leaves the pond water column and enters the pond sediments (sedimentation as organic P in the algal biomass and precipitation as inorganic P principally at pH levels above 9.5) compared to the quantity that returns through mineralization and resolubilization [74].

The efficiency of Kef el Doukhan WSP was lower than expected, particularly in terms of nutrient removal, EC and dissolved salts reduction. Wastewater's physicochemical parameters values at the outlet exceeded Algerian standards for reuse in irrigation and environmental discharges. Experimental studies on the behavior of local plants, forest trees and palm trees irrigated with the treated wastewater must be initiated. Especially, Algeria is embarking on a rehabilitation plan for the green dam realized in the 70's, a massive program of reforestation and rehabilitation in the pre-Saharan area that extends from the western to the eastern borders of Algeria. Undoubtedly, it will need a substantial quantity of plants and forest trees. To enhance the efficiency, it is reasonable to provide a tertiary treatment using maturation ponds. A series of maturation ponds (1–1.5 m deep) receives the effluent from a facultative pond. In addition, maturation ponds achieve only a small removal of BOD, but their contribution to nutrient (nitrogen and phosphorus) removal can also be significant [74]. Modifications of the pond's design by adding some additional points for wastewater inflow to the ponds to make complete mix in the different ponds are needed [84].

2.5 Conclusion

Facing water scarcity, Algerian policy is increasingly interested in unconventional water resources. Wastewater treatment and the reuse of treated wastewater has become a priority. Under the hot and arid climate of the northern Algerian Sahara, analysis of the physicochemical parameters of the influent and effluent wastewater indicated that the planted HSSFCW of Temacine was more efficient than the hybrid (HSSF and FWS) CW of Brezina and Kef el Doukhan WSP. However, in Temacine CW a relatively low effectiveness for electrical conductivity removal was observed, due essentially to the long dry season, high rate of evapotranspiration and naturally high levels of dissolved salts in water. In order to remedy this, particular attention must be paid to selecting plants with high water use efficiency to reduce evapotranspiration losses and adopting an adequate hydraulic residence time. Concerning Brezina CW, moderate removal efficiency was observed. In particular, a poor performance for total nitrogen and total phosphorus removal has been reported due to inadequate design and a lack of regular maintenance. The CW was designed without walls or physical barrier to protect the ponds against flooding and sandstorms.

Fertilizers used in the oases and sand could be transported by runoff and wind to the CW basins, which certainly affects the global removal efficiency. In addition, only one of the six basins of the CW was designed for anaerobic conditions. This design likely affected the efficiency of nutrients removal. The efficiency of Kef el Doukhan WSP was lower than expected, particularly in terms of nutrient removal, electrical conductivity and dissolved salts reduction. Wastewater's physicochemical parameters values at the outlet exceeded Algerian standards for reuse in irrigation and environmental discharges. To improve the removal efficiency, it is reasonable to provide a tertiary treatment using maturation ponds and ameliorate the design of the ponds by adding some additional points for the wastewater inflow. In contrast to Temacine planted HSSFCW, the reuse of treated wastewater of Brezina hybrid (HSSF and FWS) CW and Kef el Doukhan WSP remains unsuitable for agriculture use; it is more than necessary to review the design and consider the latest knowledge in wetland technology as well as the used plant species in these hot and arid regions.

References

1. Schilling J, Hertig E, Tramblay Y, Scheffran J (2020) Climate change vulnerability, water resources and social implications in North Africa. Reg Environ Chang 20(1):15. https://doi.org/10.1007/s10113-020-01597-7
2. Bouchekima B, Bechki D, Bouguettaia H, Boughali S, Meftah MT (2008) The underground brackish waters in South Algeria: potential and viable resources. Paper presented at the 13th IWRA World Water Congress, Montpellier, France 1–4 September 2008
3. Touitou M, Laib Y, Boudeghdegh A (2020) Management of water resources sector to face climatic shocks in Algieria: a dynamic CGE model analysis. Environ Socio-econ Stud 8(1):48–55. https://doi.org/10.2478/environ-2020-0006
4. Mozas M, Ghosn A (2013) État des lieux du secteur de l'eau en Algérie. Institut de Perspective Économique du Monde Méditerranéen (IPMED):27
5. Karef S, Boughalem M, Aitnouh F, Batana F, Boujelben N, Achak M, Oualkacha L, Kettab A (2018) Évaluation de la qualité des sous-produits de l'épuration pour usage en agriculture dans une région semi aride en Algérie. Proc JIC2017 J Maurit Chem Soc 1:12–20
6. Kettab A (2001) Les ressources en eau en Algérie: stratégies, enjeux et vision. Desalination 136(1–3):25–33
7. Office Nationale des Statistique (2019) Demographie algerienne 2019 Office Nationale des Statistique, N°890/Bis, Algerie, p1
8. Sadi A (2004) Seawater desalination share among water and market policy changes in Algeria. Desalination 165:99–104
9. Attoui B, Toumi N, Messaoudi S, Benrabah S (2016) Degradation of water quality: the case of plain west of Annaba (Northeast Algeria). J Water Land Dev 31(1):3–10

10. Hamlat A, Guidoum A (2018) Assessment of groundwater quality in a semiarid region of northwestern Algeria using water quality index (WQI). Appl Water Sci 8(8):220. https://doi.org/10.1007/s13201-018-0863-y
11. Mohammed T, Al-Amin AQ (2018) Climate change and water resources in Algeria: vulnerability, impact and adaptation strategy. Econ Environ Studi 18 (1):411-429:10.25167/ees.2018.45.23
12. Hamiche AM, Stambouli AB, Flazi S, Tayeb A (2020) Desalination in Algeria: photovoltaic power plant for TMM (Tahlyat Myah Magtaa) of Oran as a case study. In: Negm AM, Bouderbala A, Chenchouni H, Barceló D (eds) Water resources in Algeria - part II: water quality, treatment, Protection and Development. Springer, Cham, pp 285–315. https://doi.org/10.1007/698_2020_538
13. Almuktar SA, Abed SN, Scholz M (2018) Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review. Environ Sci Pollut Res 25(24):23595–23623. https://doi.org/10.1007/s11356-018-2629-3
14. Langergraber G, Regelsberger M, Eregno FE, Heistad A (2020) Design approach for treatment wetlands. In: Langergraber G, Dotro G, Nivala J, Rizzo A, Stein OR (eds) Wetland technology: practical information on the design and application of treatment wetlands. IWA Publishing, p 0. doi:https://doi.org/10.2166/9781789060171_0011
15. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
16. Benslimane M, Larbi H, Khaldi A (2016) Expérimentation d'un système de recyclage d'eaux usées urbaines phyto-epurees en milieu aride: étude de cas de Brezina (sud ouest algérien). Paper presented at the Deuxième Forum international: Évaluation, économie et protection des ressources en eau, 21 et 22 décembre 2016, Ouargla, Algerie
17. Monteverdi MC, DaCanal S, Del Lungo A, Masi S, Larbi H, De Angelis P (2014) Re-use of wastewater for a sustainable forest production and climate change mitigation under arid environments. Ann Silvic Res 38(1):22–31
18. Mandi L (1996) The use of aquatic macrophytes in the treatment of wastewater under arid climate: Marrakech experiment. In: Proceedings of the 5th International Conference on Wetland Systems for Water Pollution Control, Wien
19. Masi F, El Hamouri B, Abdel Shafi H, Baban A, Ghrabi A, Regelsberger M (2010) Treatment of segregated black/grey domestic wastewater using constructed wetlands in the Mediterranean basin: the zer0-m experience. Water Sci Technol 61(1):97–105. https://doi.org/10.2166/wst.2010.780
20. Elfanssi S, Ouazzani N, Latrach L, Hejjaj A, Mandi L (2018) Phytoremediation of domestic wastewater using a hybrid constructed wetland in mountainous rural area. Int J Phytoremediation 20(1):75–87. https://doi.org/10.1080/15226514.2017.1337067
21. Ghrabi A, Bousselmi L, Masi F, Regelsberger M (2011) Constructed wetland as a low cost and sustainable solution for wastewater treatment adapted to rural settlements: the Chorfech wastewater treatment pilot plant. Water Sci Technol 63(12):3006–3012. https://doi.org/10.2166/wst.2011.563
22. Abdel-Shafy HI, El-Khateeb MA, Regelsberger M, El-Sheikh R, Shehata M (2009) Integrated system for the treatment of Blackwater and greywater via UASB and constructed wetland in Egypt. Desalin Water Treat 8(1–3):272–278. https://doi.org/10.5004/dwt.2009.788
23. Gaballah MS, Ismail K, Aboagye D, Ismail MM, Sobhi M, Stefanakis AI (2021) Effect of design and operational parameters on nutrients and heavy metals removal in pilot floating treatment wetlands with *Eichhornia Crassipes* treating polluted lake water. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12442-7
24. Masi F (2013) Design considerations for constructed wetlands in dry and hot countries. Sustain Sanitation Pract 14:55–61
25. Nivala J, Abdallat G, Aubron T, Al-Zreiqat I, Abbassi B, Wu G-M, van Afferden M, Müller RA (2019) Vertical flow constructed wetlands for decentralized wastewater treatment in

Jordan: optimization of total nitrogen removal. Sci Total Environ 671:495–504. https://doi.org/10.1016/j.scitotenv.2019.03.376
26. Gholipour A, Zahabi H, Stefanakis AI (2020) A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. Chemosphere 247:125966
27. Mozaffari MH, Shafiepour E, Mirbagheri SA, Rakhshandehroo G, Wallace S, Stefanakis AI (2021) Hydraulic characterization and removal of metals and nutrients in an aerated horizontal subsurface flow "racetrack" wetland treating oil industry effluent. Water Res 200:117220
28. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360. S0925857421002159 106360. https://doi.org/10.1016/j.ecoleng.2021.106360
29. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, pp 25–42
30. Adhikari AR, Acharya K, Shanahan SA, Zhou X (2011) Removal of nutrients and metals by constructed and naturally created wetlands in the Las Vegas Valley. Nevada Environ Monitoring Assessment 180(1):97–113. https://doi.org/10.1007/s10661-010-1775-y
31. Greenway M (2005) The role of constructed wetlands in secondary effluent treatment and water reuse in subtropical and arid Australia. Ecol Eng 25(5):501–509. https://doi.org/10.1016/j.ecoleng.2005.07.008
32. Driche M, Abdessemed D, Nezzal G (2008) Treatment of wastewater by natural lagoon for its reuse in irrigation. Am j eng appl sci 1:408–413
33. National sanitation office (ONA) (2014) Sanitation of Ghardaia technical report. Ghardaia. Algeria :7
34. Tahar I, Sani LM, Abdelhak I, Martin S (2011) The experience of treatment of urban wastewater by lagoon in sahelian climate (Niamey – Niger) and some recent data on the implementation of this technique of treatment under climate saharan (Ouargla bowl, septentrional east algerian sahara). Algerian J Arid Environ AJAE 1, 8(2)
35. Yagoubi M, Echihabi L, Foutlane A, Bourchich L, Jellal J, Wittland C, El Yachioui M (2000) The performance of the waste stabilisation pond system at Boujaad. Morocco Water Sci Technol 42(10–11):9–16. https://doi.org/10.2166/wst.2000.0597
36. Achag B, Mouhanni H, Bendou A (2021) Hydro-biological characterization and efficiency of natural waste stabilization ponds in a desert climate (city of Assa, Southern Morocco). J Water Supply Res Technol AQUA 70(3):361–374
37. Isayed AA, Zimmo OR Effect of depth on the performance of algae-based wastewater treatment ponds. In: . Efficient management of wastewater, Springer, Berlin Heidelberg, pp 139–147
38. National Organization for Potable Water and Sanitary Drainage (NOPWASD) (2007) Environmental assessment report for New Valley governorate El Mounira and Naser El Thowra villages (Kharga oasis), Balat El Gedida and Tanidah Villages (Dakhla Oasis). Egypt
39. Berland J, Cooper P (2001) Extensive wastewater treatment processes adapted to small and medium sized communities (500 to 5000 population equivalents). Office of Official Publications of the European Union, Luxembourg
40. Hosetti BB, Frost S (1995) A review of the sustainable value of effluents and sludges from wastewater stabilization ponds. Ecol Eng 5(4):421–431. https://doi.org/10.1016/0925-8574(95)00005-4
41. Food and Agriculture Organization of the United Nations (FAO) (2012) Letter of agreement FAO: treated waste water for sustainable production of valuable biomass, soil and water quality improvement and combating desertification in Algeria and Tunisia. Intermediate report: Use of treated waste water in forestry and agroforestry systems. 10 p
42. De Angelis P, Da Canal S, Monteverdi C, Perugini L, Chiani F, Larbi H, Miloudi A, Benslimane M, Souidi Z, Nedjahi A, Khemici M, Makhlouf L, Morsli AS (2011) Nouveaux systèmes de culture pour la production agroforestière en milieu désertique par l'utilisation d'eaux usées urbaines phytoépurées: l'installation pilote - expérimentale de Brézina (Algérie). Paper pre-

sented at the Technologies vertes pour le développement durable des oasis en Algérie et la lutte contre le changement climatique . Alger, Algerie, 28.02.2011: 27
43. Cg L, Fletcher TD, Sun G (2009) Nitrogen removal in constructed wetland systems. Eng Life Sci 9(1):11–22
44. Official journal of the democratic and people's republic of Algeria (2006) Decree n ° 06–141 of April 19, 2006 regulating discharges of liquid and industrial effluents (Décret n ° 06–141 correspondant au 19 avril 2006 réglementant les rejets d'effluents liquides et industriels), vol 26 of 23-04-2006. General secretariat of the Algerian government,
45. Official journal of the democratic and people's republic of Algeria (2012) Interministerial decree of January 2012 setting the specifications of the treated wastewater used for irrigation. (Arrêté interministériel: janvier 2012 fixant les spécifications des eaux usées épurées utilisées à des fins d'irrigation.). vol 41 of 15-07-2012. General secretariat of the Algerian government, Algeria
46. Xinshan S, Qin L, Denghua Y (2010) Nutrient removal by hybrid subsurface flow constructed wetlands for high concentration ammonia nitrogen wastewater. Procedia Environ Sci 2:1461–1468. https://doi.org/10.1016/j.proenv.2010.10.159
47. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233. https://doi.org/10.1002/elsc.201600213
48. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380(1):48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014
49. Araújo AL, de Oliveira R, Mara DD, Pearson HW, Silva SA (2000) Sulphur and phosphorus transformations in wastewater storage and treatment reservoirs in Northeast Brazil. Water Sci Technol 42(10–11):203–210. https://doi.org/10.2166/wst.2000.0643
50. Bachi OE, Halilat MT, Bissati S (2015) Sewage in Algerian Oasis: comparison of the purifying efficiency of two processes (WWTP and WWTAS). Energy Procedia 74:752–759
51. Hammadi B, Seyd AH, Bebba A (2019) Performance assessment of nitrogen pollution purification by phytodepuration: case of Temacine pilot station (Algeria). Int J Environ Sci Technol 16(11):6647–6656
52. National Office of the Meteorology (ONM) (2019) National Office of the meteorology, Ministry of Public Works and Transport – metrological station of Touggourt, Touggourt, Ouargla, data of the year 2019, Algeria
53. Hammadi B, Bebba Ahmed A, Hacini Z, Zeghdi S (2013) Gardens planted with macrophytes filters, purification performance in an arid climate. Pilot station of Témacine, Ouargla (Algeria). Int Lett Chem Phys Astron 8(3):259–268
54. Riahi K, Mammou AB, Thayer BB (2009) Date-palm fibers media filters as a potential technology for tertiary domestic wastewater treatment. J Hazard Mater 161(2–3):608–613
55. Hafouda L, Hadad M, Arif Y, Djafri K, Balleche O, Talab B, Debba MS, Nelson M, Cattin F (2008) L'épuration des eaux usées domestiques par les plantes, une alternative à encourager pour une préservation durable de l'environnement en zones arides: cas de la station pilote du vieux Ksar de Témacine, Touggourt. Paper presented at the Colloque International sur l'Aridoculture, Optimisation des droductions dgricoles et développementdurable Biskra, Algerie, 13 et 14 Décembre 2008
56. Tidjani H (2019) Étude de l'efficacite et la valeur ajoutée d'un système de phytoepuration pilote en algerie: la station pilote vieux ksar Temacine, Master's thesis, Université d'el oued, pp 40 http://dspace.univ-eloued.dz/bitstream/123456789/4177/1/581.01.004.pdf
57. Cui L, Li W, Zhang Y, Wei J, Lei Y, Zhang M, Pan X, Zhao X, Li K, Ma W (2016) Nitrogen removal in a horizontal subsurface flow constructed wetland estimated using the first-order kinetic model. Water 8(11):514
58. Zhou Q, Zhu H, Bañuelos G, Yan B, Liang Y, Yu X, Cheng X, Chen L (2017) Effects of vegetation and temperature on nutrient removal and microbiology in horizontal subsurface flow constructed wetlands for treatment of domestic sewage. Water Air Soil Pollut 228(3):95. https://doi.org/10.1007/s11270-017-3280-1

59. Wagner TV, Al-Manji F, Xue J, Wetser K, de Wilde V, Parsons JR, Rijnaarts HHM, Langenhoff AAM (2021) Effects of salinity on the treatment of synthetic petroleum-industry wastewater in pilot vertical flow constructed wetlands under simulated hot arid climatic conditions. Environ Sci Pollut Res 28(2):2172–2181. https://doi.org/10.1007/s11356-020-10584-8
60. Al-Wahaibi BM, Jafary T, Al-Mamun A, Baawain MS, Aghbashlo M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. https://doi.org/10.1016/j.jclepro.2021.126558
61. Freedman A, Gross A, Shelef O, Rachmilevitch S, Arnon S (2014) Salt uptake and evapotranspiration under arid conditions in horizontal subsurface flow constructed wetland planted with halophytes. Ecol Eng 70:282–286
62. Elgallal M, Fletcher L, Evans B (2016) Assessment of potential risks associated with chemicals in wastewater used for irrigation in arid and semiarid zones: a review. Agric Water Manag 177:419–431
63. Bettahar A, Nezli IE, Kechiched R (2017) Evolution and mineralization of water chemistry in the aquifer systems of the terminal complex of the Wadi Righ Valley. Energy Procedia 119:318–324
64. Liang Y, Zhu H, Bañuelos G, Yan B, Shutes B, Cheng X, Chen X (2017) Removal of nutrients in saline wastewater using constructed wetlands: plant species, influent loads and salinity levels as influencing factors. Chemosphere 187:52–61
65. Khene B, Senoussi A, Smati FA (2012) The oasian agrosystem: characteristics and strategy evolution in the M'zab valley (Algeria). Science et changements planétaires/Sécheresse 23(2):78–85
66. Zegait R, Remini B (2018) Characterisation of treated wastewater of M'Zab Valley for reuse in irrigation (Southern Algeria). Int J Eng Res Africa 40:78–87
67. Belkhir CO, Remini B (2016) Cleanup and valuation of waters of the aquifer of M'zab valley (Algeria). J Water Land Dev 29(1):23–29
68. Benhedid H, Bouhoun MD (2018) Spatial variation of nitrogen pollution of the water table at Oued M'Zab (Northern Algerian Sahara). Paper presented at the Technologies and Materials for Renewable Energy, Environment and Sustainability,
69. Chabaca N, Kettab A, Nakib M, Karef S, Benziada S, Benmamar S, Boumalek W, Bouanani H, Djillali Y (2017) The lagunage for the purification of waste water in the Sahara: an approach integrated into the environmental conditions. Algerian J Env Sc Technol 3(2):8
70. Dubost D (2002) Ecologie, Aménagement et développement Agricole des oasis algériennes. Doctoral dissertation. Centre de recherche scientifique et technique sur les régions arides: 423
71. Benhedid H, Bensemaoune Y, Daddi Bouhoun M, Rezzag A, Geurbouz F (2018) Impact des eaux usées epurées sur la qualité des sol en aval de l'oued M'Zab. Paper presented at the 7 ème Workshop sur l'agriculture saharienne: Potentialités Agrobiologiques des Sols: Problèmes posés et Valorisation (Agro-Bio-Sol 2018). Université kasdi Merbah, ouargla, Algerie 24-May-2018 https://dspace.univ-ouargla.dz/jspui/handle/123456789/16675
72. Djaani M, Amer ZB (2020) Évaluation de la qualité des eaux usées traitées par le système de lagunage naturel d'el Atteuf et par l'argile naturelle d'el menia. UPB Sci Bull Series B 82(3):12
73. Mansouri B, Ebrahimpour M, Baramaki R (2011) Seasonal differences in treatment efficiency of a set of stabilization ponds in a semi-arid region. Toxicol Environ Chem 93(10):1918–1924
74. Mara D, Pearson H (1998) Design manual for waste stabilization ponds in Mediterranean countries. Lagoon Technology International Leeds.
75. Abdel-Rahman AM, Mohamed AA, Gad AAM, Hashem M (2013) Effectiveness of waste stabilization ponds in removal of linear alkyl benzene salfonate (las). J Urban Environ Eng 7(1):134–142
76. Boutelhig A, Melit A, Hanini S (2017) Groundwater sources assessment for sustainable supply through photovoltaic water pumping system, in M'zab valley, Ghardaia. Energy Procedia 141:76–80

77. Mkude I, Saria J (2014) Assessment of waste stabilization ponds (WSP) efficiency on wastewater treatment for agriculture reuse and other activities a case of Dodoma municipality. Tanzania Ethiopian J Environ Stud Manag 7(3):298–304
78. Mohammed Ali IA-H, Hayder Talee H (2013) Stabilization pond for wastewater treatment. Eur Sci J 9(14):278–294
79. Ouazzani N, Bouhoum K, Mandi L, Bouarab L, Habbari K, Rafiq F, Picot B, Bontoux J, Schwartzbrod J (1995) Wastewater treatment by stabilization pond: Marrakesh experiment. Water Sci Technol 31(12):75–80. https://doi.org/10.1016/0273-1223(95)00494-8
80. Wang JX (2015) Mapping the global dust storm records: review of dust data sources in supporting modeling/climate study. Curr Poll Rep 1(2):82–94
81. Machibya M, Mwanuzi F (2006) Effect of low-quality effluent from wastewater stabilization ponds to receiving bodies, case of Kilombero sugar ponds and Ruaha river, Tanzania. Int J Environ Res Public Health 3(2):209–216
82. Mahassen MEDG, Waled MES, Azza MAA, Mohammed K (2008) Performance evaluation of a waste stabilization pond in a rural area in Egypt. Am J Environ Sci 4(4)
83. Farzadkia M, Ehrampoush MH, Sadeghi S, Kermani M, Ghaneian MT, Ghelmani V, Abouee Mehrizi E (2014) Performance evaluation of wastewater stabilization ponds in Yazd-Iran. Environ Health Eng Manag J 1(1):7–12
84. Marek K, Pawęska K, Bawiec A (2021) Treatment of wastewater with high ammonium nitrogen concentration. J Ecol Eng 22(4):224–231
85. Babu M (2011) Effect of algal biofilm and operational conditions on nitrogen removal in wastewater stabilization ponds. Unesco-ihe phd thesis (1st ed.). CRC Press/Balkema,
86. Huang J, Kankanamge NR, Chow C, Welsh DT, Li T, Teasdale PR (2018) Removing ammonium from water and wastewater using cost-effective adsorbents: a review. J Environ Sci 63:174–197
87. Körner S, Das SK, Veenstra S, Vermaat JE (2001) The effect of pH variation at the ammonium/ammonia equilibrium in wastewater and its toxicity to *Lemna gibba*. Aquat Bot 71(1):71–78

Chapter 3
A Review of Constructed Wetlands Types and Plants Used for Wastewater Treatment in Egypt

Mohamed S. Gaballah, Ayman N. Saber, and Jianbin Guo

Abstract Egypt is considered one of the world's driest and most water-stressed regions. A considerable amount of wastewater produced annually in Egypt attracts a variety of treatment technologies based on several factors, most notably cost and efficiency. Natural treatment methods such as constructed wetlands (CWs) are a rapidly growing technology. CWs have been applied in Egypt for almost 30 years. Horizontal subsurface flow (HSF) CWs represent 60% of the experimental and/or full-scale and/or pilot-scale systems. In comparison, 25% of the literature refers to Free water surface (FWS) CWs, and the remaining to Vertical flow (VF) and Hybrid Systems. Water hyacinth (*Eichhornia crassipes*) as a floating plant and *Cyperus papyrus* and *Typha angustifolia* as emergent plants are widely used in CWs in Egypt. In general, CWs have shown a high treatment potential to treat wastewater under the climatic conditions of Egypt with an increasing number of applications.

Keywords Water scarcity · Wastewater · Constructed wetlands · Floating plants · Emergent plants

---

M. S. Gaballah (✉)
College of Engineering (Key Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture), China Agricultural University, Beijing, People's Republic of China

National Institute of Oceanography and Fisheries, Alexandria, Egypt

A. N. Saber
Pesticide Residues and Environmental Pollution Department, Central Agricultural Pesticide Laboratory, Agricultural Research Center (ARC), Giza, Egypt

National Engineering Laboratory for Industrial Wastewater Treatment, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China

University of Chinese Academy of Sciences, Beijing, China
e-mail: Ayman.nabil89@gmail.com

J. Guo
College of Engineering (Key Laboratory for Clean Renewable Energy Utilization Technology, Ministry of Agriculture), China Agricultural University, Beijing, People's Republic of China

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_3

3.1 Introduction

Water scarcity and wastewater management are considered significant challenges that affect the ecosystem and the urban environment worldwide. Many countries and regions worldwide continuously face growing pressure on their limited freshwater resources, particularly in arid countries such as Egypt [1]. Egypt is classified among the driest areas and the most water-stressed regions in the world, with an average annual temperature of 25 °C and even higher in summer months, and with limited annual precipitation below 250 mm, resulting in an extremely freshwater scarcity [2, 3]. Moreover, the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia threatens Egyptian water security, and negatively impacts on Egypt's freshwater since Egypt depends on the Nile River to secure 95% of its total water needs [4–8]. Thus, in Egypt, wastewater reuse is encouraged when it is safe and economically feasible to increase the water demand [9]. Several methods exist to treat wastewater based on different factors, mainly cost and efficiency, while nature-based solutions [10, 11], such as constructed wetlands (CWs), are the most growing technology.

Developing countries fail to use nature-based solutions to solve wastewater crises [1, 12]. About 95% of wastewater is discharged without treatment into lakes, seas, or other reservoirs, posing a threat to water sources and other serious environmental problems. CWs could offer an affordable and accessible solution for lower-income countries. CWs are defined as engineered eco-systems initiated and operated to treat different types of wastewater by manipulating the simultaneous physical, chemical, and biological processes [13, 14]. CWs have been rapidly developed to cover several types of wastewaters, such as municipal and industrial, due to their cost-effectiveness and eco-friendly character [1, 9, 15–20]. As a result of the growing attention to CW technology, the hydraulic design, construction, and operation have been extended to introduce various new configurations that facilitate the process as a whole and improve the performance for pollution removal [21–24, 25]. Locally, this technology has been applied in Egypt for almost 30 years.

From exploring the scientific literature, the significant number of publications related to CWs as individual experimental research or reviews on the Web of Science might be a good indicator of the increased transparency of this field's knowledge. A Web of Science database research (a tool from Clarivate Analytics, August 15, 2020) using the keyword "constructed wetlands, constructed wetlands in Egypt" resulted in 13,426 and 31 studies, respectively. This indicates that although there is a flourishing publication record available on CWs worldwide, it is limited in Egypt. Figure 3.1 depicts the number of papers per year from 2010 to 2020, showing that the topic has experienced a gradual growth in the number of studies. In addition, many books have been published recently, for instance, CWs hydraulic design [15], CWs as a suitable technology for sustainable water management [26], and CWs for industrial wastewater treatment [16].

Several review papers discussed CWs' performance in removing a wide range of pollutants from different wastewater types. These reviews have undoubtedly discussed the dynamics of pollutants, emerging organic pollutants such as antibiotics

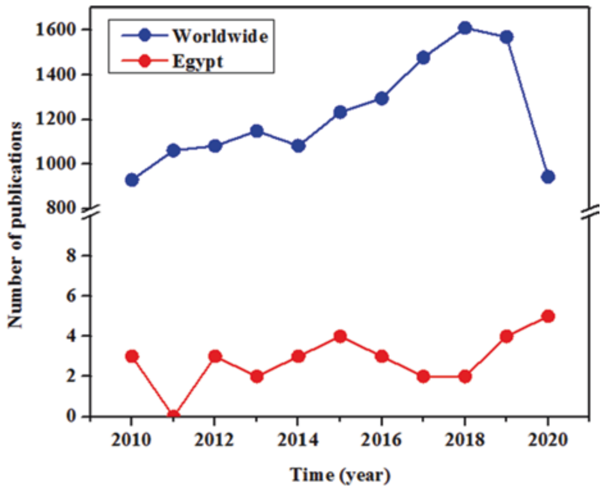


Fig. 3.1 Number of studies in the last 10 years on constructed wetlands

and pharmaceutical contaminants, and mechanisms of pollutant transformations. As a result of the increased attention to water scarcity in arid and hot regions such as Egypt, authorities have focused on wastewater reuse to protect the limited freshwater resources. Although CWs present a promising technology in Egypt, individual experiments and review papers are rarely reported.

Within this context, this chapter summarizes the current knowledge on CWs applications in Egypt along with the current status of water scarcity, taking into consideration different system configurations, operational parameters, and removal efficiencies. For this, an update on the application of CWs in Egypt is provided through a literature review of the last 10 years. Publications on CWs treating different types of wastewater in Egypt as pilot-scale and full-scale were also reviewed.

3.2 Water and Wastewater in Egypt

Egypt has a dry climate, with 95% of its area being a desert. There is a narrow strip of fertile lands alongside the major stream of the Nile and a comparatively small delta in the north [27]. It became the basis of one of the most distinctive old civilizations' societal and economic life, where the primary human activity was agriculture [28]. The total precipitation is around 25.7 mm/year; in summer, there is an evapotranspiration rate of about 0.7 mm/day. The relative humidity varies from 45–75%, and the mean daily temperature ranges from 13–38 °C. There are also limited amounts of rain and flash floods. The Nile River is Egypt's principal and almost sole freshwater supply. The country depends on Lake Nasser's accessible water to meet Egypt's annual water quota requirements, which amounts to 55.5 billion m^3/year [29].

Over the last few decades, the pollution load to the Nile system (e.g., the Nile River, canals, and drains) has grown due to population increase, many new industrial projects, and new projects for agricultural irrigation, and other activities along the Nile River. As a result, the quality of Nile water has declined significantly in the last few years [30, 31]. The Nile system's dilution capacity is likely to decrease as the policy of expanding irrigated farming progress and industrial capacity development increases the amount of pollutants discharged into the Nile [32]. The primary sources of most hazardous contaminants to the Nile and main canals are effluents from agricultural drains (including heavy metals, pesticides, fertilizers, and microbes) and the treated or incompletely treated municipal and industrial wastewaters. The most contaminated region in the Nile is between Cairo and the Mediterranean Sea within the two branches of the Nile, Rosetta and Damietta [33–35].

The industrial sector is the second essential source of water consumption and a contributor to pollution. The Egyptian factories use about 7.8 billion m^3/year of water, 4050 million m^3/year of which are discharged back to the Nile system. Hence, industrial wastewater is the second source of Nile water pollution due to hazardous organic and inorganic chemical loads in this wastewater. Industrial activities are clustered around large cities like Cairo, Giza, and Alexandria, which use 40% of total water [36]; however, small-scale private agro-industrial factories in Upper Egypt have recently begun contributing to Nile system pollution as well. Roughly 129 plants discharge their wastewater into the Nile River system. Untreated discharge of large amounts of this wastewater impacts river water used for both irrigation and drinking and has a harmful impact on aquatic life [28, 29, 37]. Food processing industries are responsible for more than 50% of the biological oxygen demand (BOD), while more than 60% of heavy metal discharges come from chemical factories. Wastewater from electroplating plants in the Helwan region (south Cairo) has a high content of Fe, Zn, Cr, Cu, and Mn [38]. Several studies have also reported the occurrence and concentration of Lead (0.001–330 μg/L) and cadmium (0.001–80 μg/L) in the Nile water [39–44]. Despite all official efforts to avoid these dangerous pollutants, 34 plants still do not comply with the Egyptian regulations for water disposal into the Nile systems [45].

The municipal wastewater effluent is considered as the third main source of Nile system pollution. The increasing population in Egypt along the Nile River leads to more wastewater generation, and policymakers are expected to expand the number of wastewater treatment plants (WWTPs). There are nearly 239 WWTPs in Egypt with an annual flow of 4.5 billion m^3, of which 1.3 billion m^3/year are discharged to the Nile water system. Toxic chemicals such as organic micro-pollutants and heavy metals are released in this wastewater because of domestic mixing with commercial and industrial activities [29]. These elevated values are higher than the standard limit and, in some areas of the Nile, higher than the permissible limits for healthy water streams. The two Nile branches, Damietta and Rosetta, downstream Delta Barrage, represent the worst River Nile quality. Some antibiotics such as sulfamethoxazole, azithromycin, and ciprofloxacin have been detected in the effluent of municipal WWTP in Beni-Suef city. Additionally, the detection of azithromycin in these municipal WWTP was higher than that detected in municipal WWTP in central Greece, China, and Thailand [46].

3.3 Constructed Wetlands (CWs)

CWs are defined as low-cost wastewater treatment techniques based on natural processes, which simulate the natural wetlands (e.g., swamps, marshes, and boglands) in a controlled environment [47]. CWs can be an effective treatment system, which can be very useful in developing countries [48], as they can remove most pollutants (e.g., pathogens, nutrients, organic and inorganic pollutants).

3.3.1 Constructed Wetland Types

As known, there are four typical types of CWs, i.e., Free water surface (FWS), Horizontal subsurface flow (HSF), Vertical flow (VF), and Hybrid Systems. In Egypt, all those types have been investigated and applied for different types of wastewaters, as shown in Table 3.1. About 60% of the experimental studies indicated that HSF is used either in full-scale or pilot-scale. HSF system in Egypt showed a high potential ability for pollutants removal compared to other systems. Approximately 25% of the reviewed literature revealed that FWS is also applied, while only one study was found on VF and another for a hybrid system.

3.3.2 Plants Used in CWs in Egypt

Local plant species can be used and grow in CWs. The plants in CWs in Egypt are classified into two types; floating plants, and emergent plants (Table 3.2).

In Egypt, the water hyacinth (*Eichhornia crassipes*) plant is an emerged plant and grows in natural waters (Lakes, Nile river, irrigation channels). It is considered an invasive aquatic weed and was found 100 years ago in the Nile Delta for the first time but entered Egypt 200 years ago. *Eichhornia crassipes* are intensively found in Northern Lakes, creating many problems such as clogging of irrigation canal intakes and flooding, disturbing the operation of hydropower and water supply systems, and resulting in the degradation of the local biodiversity [59]. It is also considered a hyper-accumulator species; however, it has many benefits, and remediation through CWs is one of them. The policies in Egypt concerning *Eichhornia crassipes* eradicating and controlling the plant from water bodies through mechanical or biological control [57], presented an efficient management scenario for its coverage percentage to enhance the phytoremediation of different pollutants and reduce the water losses instead of fall eradication. *Eichhornia crassipes* in CWs have a significant

Table 3.1 Overview of CWs applied and tested in Egypt

CW Type	Scale	Area (m^2)	Capacity (m^3/day)	Type of wastewater	Plants / media	Pollutants removal		References
						Parameter	Removal (%)	
HSF	Full-scale	231	1000	Primary treated domestic wastewater	*Cyperus papyrus* / gravel, pieces of plastic pipes, and shredded tire rubber chips	BOD	60.7	[49]
						COD	48.34	
						TSS	45.1	
HSF	Pilot-scale	181.5	8	Municipal wastewater	*Cyperus papyrus*, *Canna flaccida*, and *Phragmites australis* / gravel	BOD	83.4–88.6	[50]
						COD	83.5–89.1	
						TSS	57–68.7	
						NH_3	16–42.7	
						TKN	27–46.4	
HSF	Pilot-scale	70	2	Domestic wastewater	*Cyperus papyrus* / plastic, rubber and polystyrene foam	BOD	88	[51]
						COD	88	
						TSS	88.5	
						NH_3	78	
						P	85	
HSF	Pilot-scale	1	0.4	Polluted lake water	*Typha angustifolia* / gravel	BOD	83.3	[21]
						COD	95.8	
						Turbidity	98.4	
						NH_3	99.9	
						TN	94.7	
						TP	99.7	
						E. coli	100	
						Total bacterial count	92.3	
						Anaerobic bacteria	97.5	

HSF	Pilot-scale	654	20	Municipal wastewater	*Canna*, *Phragmites*, *Cyperus Papyrus* / gravel	BOD	91	[52]
						COD	88	
						TSS	92	
HSF	Pilot-scale	200	500	Municipal wastewater	*Phragmites australis* / gravel	BOD	89	[53]
						COD	87	
						TSS	92	
						TKN	73	
						TN	72.4	
						NH_3	76	
HSF	Pilot-scale	1.5	0.05	Agricultural and municipal wastewater	*Typha latifolia*, *Cyperus Papyrus* / gravel	BOD	68.5, 86.2	[54]
						COD	71, 85.5	
						TSS	70, 83.9	
						NH_3	82.3, 92.3	
						Bacteriological parameters	99.9	
						Salmonella sp	100	
						Cu, Zn	72, 84	
HSF-VF	Pilot-scale	10.8–9	0.4	Municipal wastewater	*Phragmites australis* / gravel	BOD	98.0	[55]
						COD	98.5	
						TSS	97.4	
						Turbidity	92.9	
						TKN	83.3	
						NH_3	93	
						TP	65.8	

(continued)

Table 3.1 (continued)

CW Type	Scale	Area (m^2)	Capacity (m^3/day)	Type of wastewater	Plants / media	Pollutants removal		References
						Parameter	Removal (%)	
VF	Pilot-scale	458	20	Primary treated municipal wastewater	*Canna*, *Phragmites australis*, and *Cyperus papyrus* /gravel	BOD	90	[48]
						COD	88	
						TSS	92	
FWS	Full-scale	125,000	21,500	Agricultural and municipal wastewater	*Phragmites australis*, *Typha latifolia*	BOD	52	[56]
						COD	50	
						TSS	87	
						NH_3	66	
						PO_4	52	
						Fe, cu, Zn, Pb	51, 36, 47, 52	
FWS	Pilot-scale	0.4	0.1	Polluted lake water	*Eichhornia Crassipes*	BOD	75	[57]
						TN	82	
						TP	84.2	
						NH_4	97.4	
						Fe, Pb, cu, Ni	62.5, 88.9, 81.7, 80.4	
FWS	Pilot-scale	0.4	0.1	Polluted lake water	*Pistia stratiotes*	BOD	83.5	[58]
						TN	90.3	
						TP	87	
						NH_4	97.53	
						Fe, Pb, cu, Ni	90.6, 97.3, 90.4, 70.2	

role in efficient nutrient absorption and high potential pollutants removal at high rates. *Pistia stratiote* is a floating aquatic plant, and its leaves spread in a rosette on the water surface that inhibits algae growth. *Pistia stratiote* is found in Egyptian waters in the spring and fall seasons. It has a high potential ability for contamination removal, as shown by [58]. *Lemna* spp. (Duckweed) the plant is an aquatic plant amongst the promising aquatic plants having the enormous capacity to treat eutrophicated wastewaters [60]; however, it's rarely used in Egypt phytoremediation studies. Duckweed is an invasive plant and is found in fresh Egyptian waterbodies. All of floating plants are used in FWS (CWs).

Cyperus papyrus plant is originated in Egypt, which has a historical benefits such as paper made and others. *Cyperus papyrus* is intensively used in CWs worldwide as a result of its high efficiency for pollutants removal [61]. Also, its root structures provide more microbial fixation sites, sufficient residence time of wastewater, entrapment, and settlement of suspended particles, the surface area for adsorption of contaminants, absorption, assimilation in plant tissues, and oxygen for the oxidation of organic matter and inorganic in the rhizosphere [62]. *Canna flaccida* is an invasive plant for the Egyptian environment; it hashing high growth rates with big roots, which may be a potential plant species that can be utilized effectively to remediate emerging organic contaminants [48, 63]. *Canna flaccida* has a colorful blossom, which can add an esthetically pleasing element to treatment sites. Phragmites are a native plant with many different species in Egypt; it usually distributes channels, lakes, and other water bodies. It has a high salinity tolerance so that it can grow on beaches.

Phragmites plant, especially *Phragmites australis* species, are widely used worldwide in CWs for treated wastewater [64]; in Egypt, many studies have used it, revealing their high ability and tolerance for heavy pollutants removal, as noted in Table 3.2. CWs widely use *Typha angustifolia* in Egypt, classified as an emergent plant with a high growth rate. *Typha angustifolia* is an invasive plant that originated from Europe and is distributed widely in many parts of the world [24]. There are many species of *typha*; *Typha angustifolia* has12–16 narrow and flat leaves [65]. *Typha angustifolia* is found in Northern lakes and the Nile River in Egypt. *Typha angustifolia* is known to have potential phytoremediation ability for various contaminants and has an antimicrobial effect against many pathogenic bacteria [22]. *Typha angustifolia* has approved its capacity for uptake the pollutants and performed efficiently in CWs. *Typha latifolia* (Cattails) is a native plant in Egypt found intensively in Lakes and the Nile River. Cattails plant has a wide range of applications, especially for its ability for pollutants removal through CWs.

3.4 Conclusions

Water scarcity and wastewater management are considered significant challenges that affect the ecosystem and the urban environment worldwide, especially in Egypt. With limited freshwater resources, Egypt has a huge amount of wastewater

Table 3.2 Plant species used in CWs in Egypt

Plant type	Plant name	Common name	Plant height	Growing season	Optimum conditions	Origin
Floating plants	*Eichhornia Crassipes*	Water hyacinth	1–2 m	Seasonally	28–30 °C	Invasive
	Pistia stratiotes	Water lettuce	0.2–0.3 m	Seasonally	22–30 °C	Invasive
	Lemna spp	Duckweed	0.01 m	Seasonally	6–33 °C	Invasive
Emergent plants	*Cyperus papyrus*	Papyrus, paper reed	4–5 m	Perennial plant	20–30 °C	Native
	Canna flaccida	Canna	1–1.5 m	Perennial plant	15 °C	Invasive
	Phragmites	Phragmites	5 m	Perennial plant	10–30 °C	Native
	Typha angustifolia	Typha	3 m	Perennial plant	25–30 °C	Invasive
	Typha latifolia	Cattails	1.5–3 m	Perennial plant	25–30 °C	Native

annually, partially treated using different methods, with Constructed wetlands (CWs) technology among them. CWs literature for wastewater treatment in Egypt has been reviewed for a period of the last 10 years. The HSF system was found to be the most widely applied system in either full-scale or pilot-scale, followed by the FWS design. Also, the commonly used plants in this technology were reviewed and showed a wide range of suitable plants growing in the Egyptian environment. This green technology has become increasingly known in Egypt and has a wide implementation potential; however, the number of publications is growing slowly. The currently limited experiences with CWs in Egypt imply the ability of this technology to contribute to addressing the water scarcity issues in Egypt effectively.

References

1. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12. https://doi.org/10.3390/w12061665
2. FAO (2014) AQUASTAT Database 2014
3. Prăvălie R (2016) Drylands extent and environmental issues. Global Approach Earth-Sci Rev 161:259–278. https://doi.org/10.1016/j.earscirev.2016.08.003
4. Abdelhaleem FS, Helal EY (2015) Impacts of grand Ethiopian renaissance dam on different water usages in upper Egypt. British J Appl Sci Technol 8(5):461–483. https://doi.org/10.9734/BJAST/2015/17252
5. Walsh D, Sengupta S (2020) For thousands of years, Egypt Controlled the Nile. A New Dam Threatens That. New York times
6. El-Nashar WY, Elyamany AH (2018) Managing risks of the grand Ethiopian renaissance dam on Egypt. Ain Shams Eng J 9:2383–2388. https://doi.org/10.1016/j.asej.2017.06.004

7. Hamada YM (2017) The grand Ethiopian renaissance dam, its impact on Egyptian agriculture and the potential for alleviating water scarcity. Environ Policy. https://doi.org/10.1007/978-3-319-54439-7
8. Abdelwahab O, Gaballahab MS, Barakata, Khouloud M, Aboagye D (2021) Pilot modified settling techniques as a novel route for treating water influent from Lake-Marriott. J Wat Proc Eng 42:101985. https://doi.org/10.1016/j.jwpe.2021.101985
9. Elzein Z, Abdou A, ElGawad IA (2016) Constructed wetlands as a sustainable wastewater treatment method in communities. Procedia Environ Sci 34:605–617. https://doi.org/10.1016/j.proenv.2016.04.053
10. Stefanakis AI, Calheiros CS, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sust 1:303–318. https://doi.org/10.1007/s43615-021-00022-3
11. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Stefania PP, Palermo A, Turco M, Pirouz B, Stefanakis A, Regelsberger M, Ursino N, Carvalho PN (2021) Management of Urban Waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334
12. Morris JC, Georgiou I, Guenther E et al (2021) Barriers in implementation of wastewater reuse: identifying the way forward in closing the loop. Circ Econ Sust 1:413–433. https://doi.org/10.1007/s43615-021-00018-z
13. Stefanakis AI (2020) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 503–525
14. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
15. Eslamian S, Okhravi S, Eslamian F (2020) Constructed wetlands: hydraulic design. CRC Press-Taylor & Francis Group, Boca Raton
16. Stefanakis AI (2018) Constructed wetlands for industrial wastewater treatment, 1st edn. Wiley, Chichester
17. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
18. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
19. Gholipour A, Zahabi H, Stefanakis AI (2020) A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. Chemosphere 247:125966
20. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
21. Andreo-Martínez P, García-Martínez N, Quesada-Medina J, Almela L (2017) Domestic wastewaters reuse reclaimed by an improved horizontal subsurface-flow constructed wetland: a case study in the southeast of Spain. Bioresour Technol 233:236–246. https://doi.org/10.1016/j.biortech.2017.02.123
22. Gaballah MS, Abdelwahab O, Barakat KM, Aboagye D (2020) A novel horizontal subsurface flow constructed wetland planted with *Typha angustifolia* for treatment of polluted water. Environ Sci Pollut Res 27:28449–25462. https://doi.org/10.1007/s11356-020-08669-5
23. Mustafa A (2013) Constructed wetland for wastewater treatment and reuse: a case study of developing country. Int J Environ Sci Dev 4. https://doi.org/10.7763/IJESD.2013.V4.296
24. Shingare RP, Nanekar SV, Thawale PR, Karthik R, Juwarkar AA (2017) Comparative study on removal of enteric pathogens from domestic wastewater using *Typha latifolia* and *Cyperus rotundus* along with different substrates. Int J Phytoremediation 19:899–908. https://doi.org/10.1080/15226514.2017.1303809

25. Al-Wahaibi BM, Jafary T, Al-Mamun A, Baawain MS, Aghbashlo M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. S0959652621007782 126558. https://doi.org/10.1016/j.jclepro.2021.126558
26. Duran-Dominguez-de-Bazua M, Del C, Navarro-Frometa AE, Bayona JM (2018) Artificial or constructed wetlands: a suitable technology for sustainable water management. CRC Press, Boca Raton
27. Abd Ellah RG (2020) Water resources in Egypt and their challenges, Lake Nasser case study. Egypt J Aquat Res 46:1–12. https://doi.org/10.1016/j.ejar.2020.03.001
28. Loutfy NM (2010) Reuse of wastewater in Mediterranean region, Egyptian experience. In: Barcelo D, Petrovic M (eds) Waste water treatment and reuse in the Mediterranean region, Hdb Env Chem. Springer, Berlin Heidelberg, pp 183–213. https://doi.org/10.1007/698_2010_76
29. Shamrukh M, Abdel-Wahab A (2011) Water pollution and riverbank filtration for water supply along River Nile, Egypt, in: Ray, C., M. Shamrukh (Eds.), pp 5–28. https://doi.org/10.1007/978-94-007-0026-0_2
30. Abdel-Dayem S, Abdel-Gawad S, Fahmy H (2007) Drainage in Egypt: a story of determination, continuity, and success. Irrig Drain 56:S101–S111. https://doi.org/10.1002/ird.335
31. Abdel-Satar AM (2005) Water quality assessment of River Nile from Idfo to Cairo. Egypt J Aquat Res 31:200–223
32. MWRI, (Ministry of Water Resources and Irrigation) (2002) Survey of Nile system pollution sources. APRP-Water Policy Activity, Ministry of Water Resources and Irrigation (MWRI), EPIQ Report No. 64
33. Abdo MH (2004) Environmental studies on the River Nile at Damietta branch region. Egypt J Egypt Acad Soc Environ Dev Stud 5:85–104
34. NAWQAM (1998) Present status of water quality in Egypt. National Water Quality and availability management project (NAWQAM), National Water Research Centre, Canadian Executive Agency, Assessment Interim Report
35. NAWQAM (2003) Nile research institute data. National Water Quality and availability management project (NAWQAM), National Water Research Centre. Egypt
36. Wahaab RA, Badawy MI (2004) Water quality assessment of the River Nile system: an overview. Biomed Environ Sci 17:87–100
37. Elbana TA, Bakr N, Elbana M (2019) Reuse of treated wastewater in Egypt: challenges and opportunities. Handb Environ Chem 75:429–453. https://doi.org/10.1007/698_2017_46
38. El-Rafei S, El-Shawarby SI, Fahim FA (1987) Heavy metals in wastewater to the Nile. Desalination 67:355–362. https://doi.org/10.1016/0011-9164(87)90254-2
39. Ali MM, Soltan ME (1999) Heavy metals in aquatic macrophytes, water and hydrosoils from the river Nile. Egypt J Univ Arab Biol:99–115
40. Elsokkary IH, Müller G (1990) Assessment and speciation of chromium, nickel, lead and cadmium in the sediments of the River Nile. Egypt Sci Total Environ 97–98:455–463. https://doi.org/10.1016/0048-9697(90)90256-T
41. Gomaa MNE (1995) Recycling study of some heavy metals in the Egyptian aquatic ecosystem. Food Chem 54:297–303. https://doi.org/10.1016/0308-8146(95)00050-S
42. Mohamed MAM (1998) Environmental pollution of River Nile and drinking water by pesticides and heavy metals, Ph. D. thesis, Biochemistry Department, Cairo University, Egypt
43. Rashed MN (2001) Monitoring of environmental heavy metals in fish from Nasser Lake. Environ Int 27:27–33. https://doi.org/10.1016/S0160-4120(01)00050-2
44. Soltan ME, Awadallah RM (1995) Chemical survey on the River Nile water from Aswan into the outlet. J Environ Sci Heal Part A Environ Sci Eng Toxicol 30:1647–1658. https://doi.org/10.1080/10934529509376293
45. NBI (2005) Nile Basin water quality monitoring baseline report. Transboundary Environmental Action Project, Nile Basin Initiative
46. Younes HA, Mahmoud HM, Abdelrahman MM, Nassar HF (2019) Seasonal occurrence, removal efficiency and associated ecological risk assessment of three antibiotics in a municipal

wastewater treatment plant in Egypt. Environ Nanotechnol Monit Manag 12:100239. https://doi.org/10.1016/j.enmm.2019.100239
47. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380:48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014
48. Abou-Elela SI, Hellal MS (2012) Municipal wastewater treatment using vertical flow constructed wetlands planted with *Canna*, *Phragmites* and *Cyperus*. Ecol Eng 47:209–213. https://doi.org/10.1016/j.ecoleng.2012.06.044
49. Zidan ARA, El-Gamal MM, Rashed AA, El-Hady Eid MAA (2015) Wastewater treatment in horizontal subsurface flow constructed wetlands using different media (setup stage). Water Sci 29:26–35. https://doi.org/10.1016/j.wsj.2015.02.003
50. Abou-Elela SI, Hellal MS, Elekhnawy MA (2019) Phytoremediation of municipal wastewater for reuse using three pilot-scale HFCW under different HLR, HRT, and vegetation: a case study from Egypt. Desalin Water Treat 140:80–90. https://doi.org/10.5004/dwt.2019.23362
51. Khalifa ME, Gaber Y, El-Reash A, Ahmed MI, Rizk FW (2020) Effect of media variation on the removal efficiency of pollutants from domestic wastewater in constructed wetland systems. Ecol Eng 143:105668. https://doi.org/10.1016/j.ecoleng.2019.105668
52. Abou-Elela SI, Golinelli G, El-Tabl AS, Hellal MS (2014) Treatment of municipal wastewater using horizontal flow constructed wetlands in Egypt. Water Sci Technol 69:38–47. https://doi.org/10.2166/wst.2013.530
53. Abdel-Shafy HI, El-Khateeb MA (2013) Integration of septic tank and constructed wetland for the treatment of wastewater in Egypt. Desalin Water Treat 51:3539–3546. https://doi.org/10.1080/19443994.2012.749585
54. Hamad MTMH (2020) Comparative study on the performance of *Typha latifolia* and *Cyperus Papyrus* on the removal of heavy metals and enteric bacteria from wastewater by surface constructed wetlands. Chemosphere 260:127551. https://doi.org/10.1016/j.chemosphere.2020.127551
55. Abdel-Shafy HI, El-Khateeb MA, Shehata M (2017) Blackwater treatment via combination of sedimentation tank and hybrid wetlands for unrestricted reuse in Egypt. Desalin Water Treat 71:145–151. https://doi.org/10.5004/dwt.2017.20538
56. El-Sheikh MA, Saleh HI, El-Quosy DE, Mahmoud AA (2010) Improving water quality in polluted drains with free water surface constructed wetlands. Ecol Eng 36:1478–1484. https://doi.org/10.1016/j.ecoleng.2010.06.030
57. Gaballah MS, Ismail K, Aboauge D, Ismail M, Sobhi M, Stefanakis AI (2021) Effect of design and operational parameters on nutrients and heavy metal removal in pilot floating treatment wetlands with *Eichhornia Crassipes* treating polluted lake water. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12442-7
58. Gaballah MS, Ismail K, Beltagy A, Zein Eldin AM, Ismail MM (2019) Wastewater treatment potential of water lettuce (*Pistia stratiotes*) with modified engineering design. J Water Chem Technol 41:197–205. https://doi.org/10.3103/s1063455x1903010x
59. Sasaqi D, Setyono P (2019) Estimation of water losses through evapotranspiration of water hyacinth (*Eichhornia crassipes*). Caraka Tani J Sustain Agric 34:86–100
60. Iqbal J, Javed A, Baig MA (2019) Growth and nutrient removal efficiency of duckweed (*lemna minor*) from synthetic and dumpsite leachate under artificial and natural conditions. PLoS One 14:1–9. https://doi.org/10.1371/journal.pone.0221755
61. Alufasi R, Parawira W, Stefanakis AI, Lebea P, Chakauya E, Chingwaru W (2022) Environ Technol 43(7):949–961. https://doi.org/10.1080/09593330.2020.1811395
62. García-Ávila F, Patiño-Chávez J, Zhinín-Chimbo F, Donoso-Moscoso S, Flores del Pino L, Avilés-Añazco A (2019) Performance of *Phragmites Australis* and *Cyperus Papyrus* in the treatment of municipal wastewater by vertical flow subsurface constructed wetlands. Int Soil Water Conserv Res 7:286–296. https://doi.org/10.1016/j.iswcr.2019.04.001
63. Hwang JI, Li Z, Andreacchio N, Ordonez Hinz F, Wilson PC (2020) Potential use of floating treatment wetlands established with *Canna flaccida* for removing organic contaminants from surface water. Int J Phytoremediation 22:1304–1312. https://doi.org/10.1080/15226514.2020.1768511

64. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360. S0925857421002159 106360. https://doi.org/10.1016/j.ecoleng.2021.106360
65. Sricoth T, Meeinkuirt W, Pichtel J, Taeprayoon P, Saengwilai P (2018) Synergistic phytoremediation of wastewater by two aquatic plants (*Typha angustifolia* and *Eichhornia crassipes*) and potential as biomass fuel. Environ Sci Pollut Res 25:5344–5358. https://doi.org/10.1007/s11356-017-0813-5

Chapter 4
Two Decades of Experience on Nature-Based Solutions for Wastewater Treatment in Egypt, Palestine and Tunisia

F. Masi, A. Rizzo, N. Martinuzzi, and R. Bresciani

Abstract A few nature-based wastewater treatment plants (WWTP) designed in three arid countries, i.e. Egypt, Palestine and Tunisia are presented in this chapter, with a focus on the potential of treated wastewater reuse in line with circular economy concepts. All the presented systems are Horizontal Subsurface Flow (HF) Constructed Wetlands (CWs) (Egypt, Palestine), Vertical Flow (VF) CWs (Palestine), or multistage CWs combining HF and VF stages (Tunisia, Palestine). The CW WWTPs operate in the range of about 50–5000 PE and all cases include reuse as the main final destination of the treated effluents. Almost twenty years of direct experience in these hot or arid climate countries, lately extended to new projects in India, Indonesia, Cambodia, have generated some useful indications for the design of nature-based solutions (NBS) in such operational scenarios, duly reported in the following discussion.

Keywords Nature-based solutions · Constructed wetlands · Treatment wetlands · Sustainable sanitation · Sustainable water management · Wastewater reuse · Circular economy · Egypt · Palestine · Tunisia

4.1 Introduction

Constructed/treatment wetlands (CWs or TWs) are engineered water treatment systems that optimize the multiple transformation processes of chemical compounds present in natural environments, with particular focus on the ones defined as pollutants. CWs efficiently treat different kinds of polluted water [1–3]. Compared to conventional systems, CWs are large and extensive systems which require only minimal effort in operation and maintenance. This operational aspect makes CWs

F. Masi (✉) · A. Rizzo · N. Martinuzzi · R. Bresciani
IRIDRA Srl, Florence, Italy
e-mail: masi@iridra.com

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_4

suitable solutions for wastewater treatment in remote areas [4, 5]. Nowadays there are several applications of CWs in hot and dry climate countries, and very often in these specific locations [6–11, 12–14] reuse is one of the main design targets and thus water loss should be minimised, for instance by selecting plants with low evapotranspiration (EP) capacity or CWs technologies that reduce the retention time or the areal footprint, and the consequent losses due to evaporation (ET) and EP [15, 14]. Therefore, CWs typologies such as those with subsurface flow, where the air/water interface is not direct, can surely be preferred to open water systems, still having water reuse as a main goal. On the contrary, the higher ET and EP performances that can be obtained in arid climate locations can also be used to aim for zero-discharge systems, sometimes a wise choice when dealing with particular industrial wastewaters or in cases with specific constrains.

The latest trends in sustainable water cycle design are everywhere focused on resource recovery approaches, where said resources are represented by treated water, up to desired performance levels, and nutrients (N and P, both in chemical species ready-to-use as fertiliser) [16, 17]. In arid countries this approach is of primary importance to secure food production in the coming decades. NBS coupled with fertigation of crops (agroforestry, high value plants, biomasses for biorefineries or for direct or indirect energy production) could be an effective way to cover the still too large percentage of untreated and not properly managed domestic wastewater in today's world [18].

4.2 IRIDRA Experience on NBS in Hot and Dry Climates

Over the last 15 years, IRIDRA's multi-disciplinary team of experts in nature-based solutions (NBS) has often been involved in the design of NBS for wastewater treatment and reuse in arid climates. In particular, the nature-based wastewater treatment plants (WWTP) designed in three arid countries, namely Egypt, Palestine and Tunisia will be presented, with particular attention to the potential of treated wastewater reuse in line with the concepts of circular economy. Moreover, the examples presented also have a wide variability in terms of technologies used, since both single stage combinations (horizontal subsurface flow – HF, vertical subsurface flow – VF) and different multistage combinations were designed.

The Egyptian case study is a CW for domestic wastewater treatment and reuse for irrigation purposes. The wastewater is generated by a farm located in the Sharquiya Governorate, in the Nile Delta region, which produces organic and pharmaceutical plants, and includes a primary school, training workshops, offices, a communal laundry and a few houses.

The Tunisian case studies consist of a multistage Treatment Wetland system for the rural village of Chorfech of 500 inhabitants and a primary school located nearby which is equipped with a small constructed wetland and all feasible water-saving devices, including the reuse of the treated wastewater for toilet flushing.

Three main case studies will be presented for Palestine, amongst the numerous Palestinian experiences of IRIDRA both in the Gaza strip and in the West Bank, namely the CW WWTP for the villages of Hajja and Sarra, and the CWs for treatment and reuse of grey water for Bedouin villages. The Sarra CW WWTP serves 4300 p.e. and it is aimed at treating wastewater for reuse in the cultivation of olive trees, or for discharge into open freshwater. The Hajja CW WWPT has a treatment capacity of 700 p.e., and is also aimed at discharging into a ditch. Finally, grey water CW treatment systems were implemented to serve Bedouin villages in southern Palestine, a very arid and deserted area, as part of an OXFAM action financed by EU (ECHO), FAO and the Sardinia Region; the treated grey water is reused for the irrigation of olive cultivation and fodder (Table 4.1).

4.2.1 Chorfech, Tunisia

Chorfech is a rural settlement of 50 houses inhabited by 500 people and a similar number of domestic animals, located 24 km NW of Tunis, Tunisia. 40% of the Tunisian population lives in small villages or isolated habitats with access to drinking water for almost all (~ 94%). 83% of this population lives with poor sanitation services and their wastewaters is discharged directly without treatment. Only 3.2% of the rural populations have a sewer system, and 13.5% have a sanitary pit or septic tank. For these reasons, the Tunisian government is now interested in the development of sanitation in small and rural villages, where the current sanitation poses a serious risk to the environmental and human health. The necessary technologies must be as robust, simple and low-tech as possible, and must be able to provide a high quality of treated wastewater.

This region of northern Tunisia has an average rainfall of about 470 mm/year, with temperatures ranging from average daily values of 13.7–28.3 °C.

Before the construction of the WWTP, the raw wastewater was collected in a conventional combined sewer and discharged into a drainage channel after a primary sedimentation in a septic tank. A multistage CW, consisting of three stages HF + VF + HF, was implemented to serve the village and put in operation in 2009. The multistage CW receives effluents from an Imhoff tank, whose primary sludge is pumped twice a year into a Sludge Drying Reed Bed (still a NBS similarly designed to VF CWs with all the needed adaptations to deal with the sludge dehydration and composting on-site) positioned nearby. The leachate produced by the SDRB is recirculated by a drainage system to the first stage HF (Fig. 4.1 and Table 4.2).

The removal rates performed by the WWTP of Chorfech during the monitored period were respectively: 97.12% for TSS, 94.56% for COD, 97.22% for BOD_5, 71.39% for total Nitrogen, 82.15% for total Phosphorus. The removal of the *E. coli* and Enterococcus by the whole system ranged from 1.8 to 2.5 log units. Treated water complies with the local normative limits for agricultural reuse (for instance orange trees plantations or fodder production) and the best practice is to bypass the third stage, aimed at removing Nitrogen from the effluents by denitrification, to

Table 4.1 Summary of design data for the case studies

Parameter	Unit	Palestine (6 small plants)	Sarra, Palestine	Hajja, Palestine	Sekem, Egypt	Chorfech, Tunisia
Size	PE	70–120	3500	1200	250	350
Flow	m^3/d	4–8	350	120	20	15–20
Mechanical pre-treatment	–	Degreaser	Automatic screw screen +2 Imhoff tanks in parallel	Three chamber septic tank + manual grid	Manual grid +3-chambers septic tank	Manual grid + Imhoff tank
Type of CW	–	VF	VF 1st stage HF 2nd stage	VF + HF	HF	HF + VF + HF
Total surface	m^2	30–60	Total: 4500 VF: 1500 HF: 3000	Total: 1590 VF: 615 HF: 975	200	Total: 1800 HF 1st: 200 VF 2nd: 850 HF 3rd: 750
OLR	$g_{BOD}/m^2/d$	15–37	Total: 65 VF: 197 HF:20	Total: 53 VF: 138 HF: 8	75	13
HRT	D	–	2	2.4	2.3	–
Irrigation reuse		Fodder	Olive tree	Olive tree	Timber plantation	Fodder – Orange trees
Latitude	°	31°22′32.4”N	32°12′44.7”N	32°11′54.9”N	30°25′15.1”N	36°57′08.9”N
Max monthly ET0[a]	cm/d	0.50	0.51	0.52	0.62	0.51

[a]Potential evapotranspiration or reference crop (ET0) estimated with the Thorntwaite method, mean monthly temperature: climate-data.org

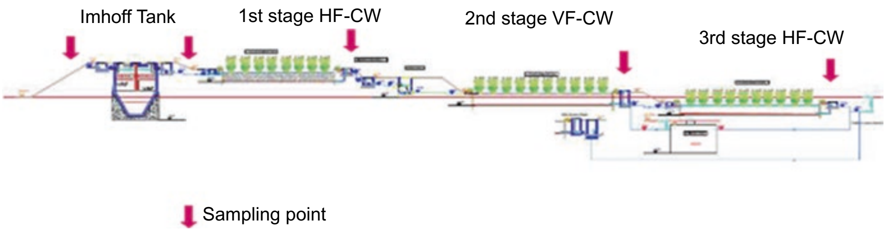


Fig. 4.1 Hydraulic profile of the Chorfech CW WWTP I nTunisia

Table 4.2 Performances of the Chorfech CW WWTP in Tunisia (average values of about 8 sampling events - grab samples)

Measured flow: 17 m^3/d	COD (mgO_2/L)	BOD_5 (mgO_2/L)	TSS (mg/L)
Raw WW	3072	1620	1407
Imhoff tank	2876	1350	956
HF first stage	1647	197	174
VF second stage	234	26	86
HF third stage	167	45	53
Removal (%)	**94.6**	**97.2**	**96.2**

increase the concentrations of Nitrates and Phosphates in the effluent to provide water and nutrients to the crops in spring and summer. In the autumn and winter seasons, there is no need for fertigation and therefore the effluent must be discharged into freshwater (an artificial drainage channel) and the denitrification is needed to reach the specific values allowed for Total Nitrogen.

4.2.2 Chorfech Primary School, Tunisia

A pilot demonstration installation was also implemented at the Chorfech school (Fig. 4.2). The objectives were: (i) to solve the problem of the uncontrolled discharge of domestic wastewater, and (ii) to identify a robust and simple solution to be recommended for application in rural schools in Tunisia, characterized by limited financial resources for water supply and sanitation. Several tools for water saving (push-button taps, waterless urinals, rainwater harvesting) are part of the installation. The sanitation system consists of a septic tank followed by a HF CW. The treated effluent is reused for gardening.

During the monitored period the school hosted 7 teachers and a number of students between 65 and 74 per year. The average consumption of drinking water was just over 21 L/day/student, after the implementation of the demonstrative installations, it decreased by over 50% (10.7 L/day/student). The averages of the overall removal rates of the "Septic Tank – HF CW" sanitation system were equal to 93% for TSS, 86,7% for COD, 96,4% for BOD_5, 68% for NH_4^+, 71% for TKN, 88,5% for

Fig. 4.2 Implementation of water saving equipment (push-button taps, urinal waterless, and rainwater reservoir, general layout of sanitation and HF CW) at the Chorfech school in Tunisia

PO_4^{3-}. Evidence has shown that this solution can be recommended for a wide range of applications in rural schools in Tunisia and could be replicated in similar areas and countries in order to save water and to efficiently treat domestic wastewater, avoiding the direct discharge of untreated wastewater.

4.2.3 Hajja and Sarra, Palestine

Water supply systems for villages and farmland are a complex problem across the West Bank in Palestine. The shortage of water and the impossibility of building a distribution and irrigation system entails a great difficulty for local agricultural development and consequently the general economic situation. In the area of Nablus and Qalqylia, olive cultivation is one of the traditional activities and sources of income that is most affected by this water shortage. The implementation of CW based WWTPs for both villages, producing fertilisers-rich effluents for olive plantations, was therefore intended to improve the living conditions of the population by increasing the economic role played by these crops, especially through the sale of olive oil with a more stable trend of the annual yields linked to a more constant availability of water and nutrients for the fertigation of the plantations. The WWTPs implementation was funded by the project “Making wastewater an asset: increasing agricultural production introducing irrigation by non-conventional water sources” managed by the NGOs GVC-Italy (WeWorld), PHG and UAWC (Palestine) and financed by the EU (Contract number DCI-FOOD/2010/254-819).

The WWTP in Sarra (about 3500 PE) is a 2-stage CW system, with a pre-treatment with mechanical screen, a primary treatment with two Imhoff tanks in parallel, a secondary treatment with first stage VF CW (6 basins in parallel, 1500 m^2), second stage HF CW (6 basins in parallel, 3000 m^2). The system is equipped with SDRBs for the primary sludge from the Imhoff (Fig. 4.3).

The WWTP in Hajja also has the same configuration, VF + HF CW (after a primary grid and a primary treatment with Imhoff tanks), installed as an upgrade of an

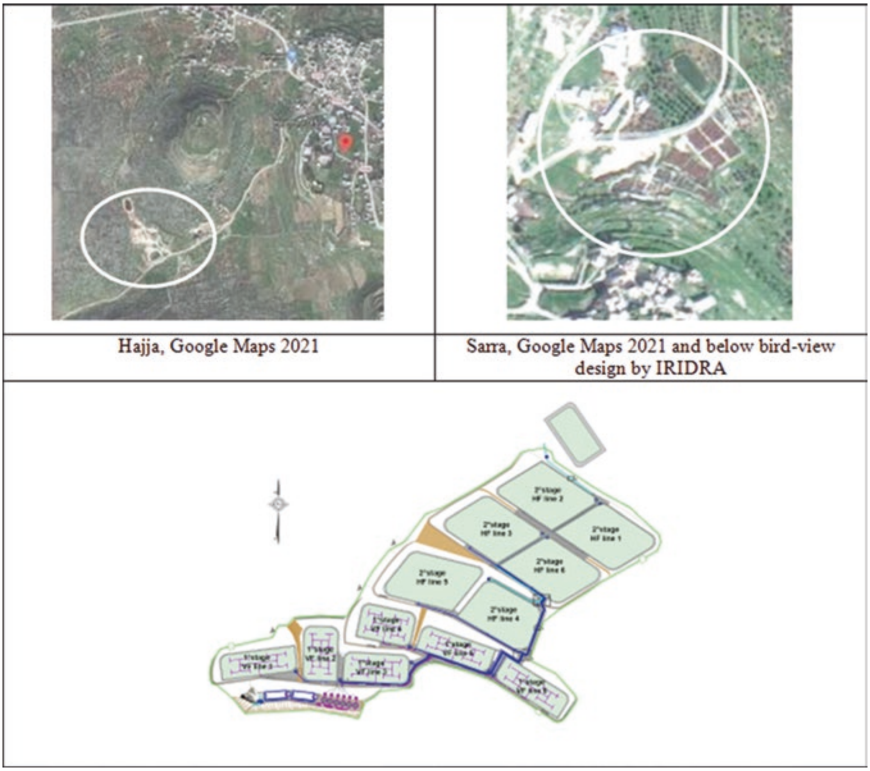


Fig. 4.3 Areal views of Hajja and Sarra CW WWTP as well as Sarra CW WWTP plan layout in Palestine

existing HF CW serving a population of about 1000 PE and designed to have the possibility to be doubled with the construction of two other identical lines as the remaining part of the population (up to 3000 PE) will be connected to the treatment system. In both WWTPs the effluents will be stored in ponds, deep and shaded, and reused for the fertigation of olive trees.

In the related FAO Report (2014), the following results obtained by the 2 NBS installations are listed:

1. reclaimed wastewater, complying with minimum standards for agricultural reuse, are made available to farmers through the construction and the rehabilitation of efficient and sustainable sanitation systems for the villages of Sarra and Hajja;
2. village Councils are able to manage and maintain the sanitation systems and general public and farmers are aware of the main issues of sustainable and environmentally sound sanitation including reuse of treated wastewater, through capacity building and awareness-information programmes;
3. the irrigation with treated effluent and the application of efficient farming practices has increased.

The construction of a sewer collection system and a WWTP in Sarra, and the rehabilitation of the existing CW in Hajja were supported by several parallel activities such as capacity building of the village councils for the financial management of the sanitation systems, activities raising awareness of the public and farmers, technical training on olive cultivation, orchard management and olive oil quality, provision of irrigation network tools and equipment, improvement of marketing practices.

4.2.4 Palestinian Bedouin Villages

Oxfam Italy assigned to IRIDRA the design of several CWs for the treatment of greywater in some Palestinian villages in the southern regions of the West Bank. The greywater treatment implementations were inserted into projects funded by EC and other sponsors for emergency support to herder and Bedouin communities. Since 2008, some NGOs operating in the West Bank and in Gaza, have started introducing CW technology in Palestine, with the main aim of creating a new alternative water source to reduce the water stress typical of that area in recent years and to enhance the local economy with the increase of the farming capacity in herders' villages or of the agricultural productivity (focusing mainly on the cultivation of olive trees). The CW systems in some cases treat mixed wastewater from small groups of houses, in others greywater only, considering anyway a per-capita consumption ranging from 9 to 15 L/d. The final effluent is then used to drip-irrigate pieces of arid land for fodder production (bushes with low water demand), since the local economy is mainly based on goat breeding and water scarcity is one of the most important limiting factors for its improvement. The CW systems are designed to minimize the loss of water by evapotranspiration and to provide the easiest maintenance, mainly single stage VF CWs, also because the systems are managed directly by the village councils, with the direct involvement of the community members (Fig. 4.4).

These first experiences have shown promising results and a good acceptance of the CW technique by the served population and local authorities and these factors together could ensure a widespread diffusion of this type of approach in the coming years.

4.2.5 Sekem School, Egypt

In the early years of the new century, full scale CWs were not well known in Egypt, with few exceptions. The WWTP of the SEKEM farm was designed for wastewater treatment and reuse for fertigation of agroforestry plots. The wastewater is composed of 100% domestic wastewater; the daily flow was calculated both

Fig. 4.4 Ramadin VF CW system for greywater reuse in Palestine

on the basis of water demand and on the basis of the number of people connected: 500 students at 20 L/day, plus 100 persons in the offices at 20 L/day, laundry plus residential houses leading for a total of 15 m^3/day. The SEKEM administration considered a possible extension of the school and boarding school leading to a design flow of approximately 20 m^3/day. The HF CW, implemented in 2007, has a total surface of 200 m^2. The effluents are reused on timber plantations for the packaging of the SEKEM products (mainly medicinal herbs and extracts). The area of the study is located East of the Sharquiya Governorate. Thirty years ago, this area was a desert with no agriculture activity. One of the Farm's sewage systems serves schools and boarding school, training workshops, offices, laundry and few houses. The project was designed to implement and construct real integrated models of wastewater treatment and reuse for the peri-urban and deprived remote regions.

From a monitoring campaign, for a total of 30 sampling events, the quality of the treated wastewater was found to be within the Egyptian standards allowed for the irrigation of timber plantations. No problems with odours or insects were reported and improved water reuse and groundwater protection were obtained. The overall removal of the WWTP exhibited a remarkable improvement in the characteristics of the treated wastewater reaching 73, 92 and 91% respectively for TKN, TSS, VSS, in addition to 89% for BOD_5 and 87% for COD. About 16 m^3/d of freshwater were saved by reusing efficiently treated wastewater to irrigate the agricultural area.

4.3 Conclusions: Lessons Learnt

In the following paragraphs the main findings and reflections generated by the direct field experience in the design, construction supervision and monitoring in the following years are discussed and proposed for further elaboration.

4.3.1 Design Recommendation

In several case studies, and in particular in those with a warmer climate, the measured inlet concentrations of the main pollutants were notably higher than the usual values for domestic wastewater, due to lower water consumption and evaporation of the wastewater itself. These high inlet concentrations coupled with low flows must be considered in the sizing equations, properly considering the temperature effects on the kinetics of the transformation processes of the pollutant molecules. Organic loads of CWs in hot countries can be higher compared to temperate climates. The available results, even though referred to a few experiences, show that the organic load can reach values up to 10–30 times higher than the usual ranges applied in Europe or North America.

A second common issue related to the hot climate is that, especially during the first months of construction, all the plastic parts exposed to sunlight (e.g. feeding pipes in PVC, HDPE geomembrane over the embankments) must be adequately protected and shaded in order to avoid deformations or premature aging of the polymers.

Plants, on the other hand, are more prone to water stresses; careful management is required in case of prolonged periods without water users and consequently WWTP users (e.g. touristic sites). Emergency irrigation is sometimes needed during these dry periods to maintain vegetation alive, in particular in VF systems; HF systems also need to be irrigated usually after 2–3 weeks with no inlet flow.

Still relating to vegetation, the initial plantation can be more successful (a low mortality rate for planted rhizomes or small plants) with a well-conducted commissioning phase where the water level is kept high, such as 2–3 cm over the bed surface.

As a last advice, mainly based on direct experience in such scenarios, a simpler construction and operation system, such as a HF CW, is preferable in remote areas and in situations with a high fluctuation of the inlet hydraulic and organic loads, for the greater volume of water contained in the reactor and the consequent more efficient buffering effect. Even a lower dependence on technical components such as electromechanical pumps or even siphons can ensure in such remote locations a more robust behaviour in time (Table 4.3).

Table 4.3 Summary of special considerations during the design phases from direct experience in case studies

Case studies	Lessons learnt during design
Palestine: 6 small plants	VF system are preferred to HF systems in order to minimize ET losses and enhance the treatment flexibility due to the high fluctuations in daily hydraulic and organic loads
Palestine: Sarra and Hajja	Due to the limited available area, a hybrid system was equipped with a VF 1st stage filled with pea gravel (according to French systems guidelines) designed for high loading rates and gravity fed via siphon devices. This design choice was also made with the goal of reducing ET losses. A final pond was created to store the treated water and to refine its quality.
Egypt: Sekem	The high fluctuations of the loads during the week led to the selection of robustness and high buffering capacity, combined with the lower needs in ordinary and extraordinary maintenance of the system; in these cases, a HF CW complies with the above-mentioned requirements.
Tunisia: Chorfech	Modularity is a must whenever the final fate of the effluent varies throughout the year and also when the loads follow seasonal trends. In particular, when reuse for fertigation is the only discharge in the summer months, nutrients are welcome in controlled concentrations, while very often they are not if the effluent has to be discharged in a water body in winter; this operational approach can be made possible by the selection of a treatment train including multiple stages, each with specific processing functions, with the possibility of disconnecting and by-passing the different stages as needed; a well-conceived O&M Manual is desirable, for the proper maintenance of all stages of the system in all the different operation scenarios.

The following general considerations should be all properly checked in the preliminary phase of the design:

1. when TWW is going to be reused, the WW treatment efficiency should match the quality necessary for the specific reuse purpose, limiting the treatment performances to what is really necessary; WW segregation and on-site treatment of greywater can efficiently contribute to the production of a safe effluent with the proper quality available for the targeted reuse;
2. VF might be preferred to HF CWs to minimize EP and ET losses due to their intrinsic shorter HRT in comparison to other CW typologies; depending on the required effluent quality and reuse aim, the VF beds can be filled with coarser sand, down to the smallest gravel available on site, in order to reduce the retention time (as well as the performances in terms of pollutants removal);
3. HF CWs are simpler in construction and operation as no intermittent loading is required and enhance the treatment robustness and flexibility whenever there is high fluctuation in HLR and OLR, due to the large quantity of water stored in the gravel bed, if compared to the inlet flow, and the related buffering effect.

4.3.2 Implementation

Often, in remote areas of low-income countries, the main difficulties are linked to the supply of the components for the implementation of the NBS. In small systems, frequently implemented by unskilled workers, proper quality in the positioning of the liners is not always guaranteed.

In several countries the use of siphons for the feeding of VF CWs is introducing a higher weakness, in terms of robustness and lifetime of the WWTP, compared to the use of electric pumps, generally better known and more easily replaceable or repairable in case of malfunctioning.

Furthermore, proper construction supervision by CW experts is suggested for a successful implementation, including in the project budget and activity plan a sufficient number of construction site visits by said experts, especially during the most sensitive implementation activities (e.g., soil movements, physical definition of the hydraulic profiles, geomembrane posing, piping, installation of control manholes).

4.3.3 Water Reuse

As already detailed in the previous paragraphs, the following suggestions should be considered for a successful implementation of water cycles in arid countries:

- unsaturated VF are preferable to HF CWs to limit EP and ET losses (shorter HRT);
- mass balances are needed to check the possible concentration of a target pollutant to meet the specific water quality standard for reuse (e.g. salt concentrations)
- the segregation between grey and black water can contribute to the production of goods through their processing, "new water" by treating greywater and fertilisers or energy from concentrated black water.

References

1. Kadlec RH, Wallace S (2009) Treatment wetlands, 2nd edn. CRC press, Boca Raton
2. Dotro G, Langergraber G, Molle P et al (2017) Treatment wetlands. IWA publishing
3. Langergraber G, Dotro G, Nivala J et al (eds) (2019) Wetland technology: practical information on the design and application of treatment wetlands. IWA publishing
4. Masi F, Martinuzzi N, Bresciani R et al (2007) Tolerance to hydraulic and organic load fluctuations in constructed wetlands. Water Sci Technol 56(3):39–48
5. Masi F, Langergraber G, Santoni M et al (2020) Possibilities of nature-based and hybrid decentralized solutions for reclaimed water reuse. In: Verlicchi P (ed) Advances in chemical pollution, environmental management and protection, vol 5. Elsevier, pp 145–187
6. Masi F, El Hamouri B, Abdel Shafi H et al (2010) Segregated black/grey domestic wastewater treatment by constructed wetlands in the Mediterranean basin: the Zer0-m experience. Water Sci Technol 61(1):97–105

7. Aubron T, Nivala J, Headley TR, et al (2012) Suitability of treatment wetlands for water-scarce countries: a case study in Jordan. In: Proceedings of the 13th IWA Specialized Group Conference on Wetland Systems for Water Pollution Control. Perth, WA, Australia, 25–29 November
8. Mandi L, Bouhoum K, Ouazzani N (1998) Application of constructed wetlands for domestic wastewater treatment in an arid climate. Water Sci Technol 38(1):379–387
9. Masi F, Martinuzzi N (2007) Constructed wetlands for the Mediterranean countries: hybrid systems for water reuse and sustainable sanitation. Desalination 215(1–3):44–55
10. Abdel-Shafy HI, El-Khateeb MA, Regelsberger M et al (2009) Integrated system for the treatment of Blackwater and greywater via UASB and CW in Egypt. Desalination Water Treat 8:272–278
11. Abdel-Shafy HI, Dewedar A, Bahgat MM (2006). Wastewater treatment via reed bed system in Ismailia, Egypt. In: International Conference on Wateraqua, Marakish, June
12. Al-Wahaibi BM, Jafary T, Al-Mamun A, Baawain MS, Aghbashlo M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. S0959652621007782 126558. https://doi.org/10.1016/j.jclepro.2021.126558
13. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360. S0925857421002159 106360. https://doi.org/10.1016/j.ecoleng.2021.106360
14. Stefanakis A (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
15. Headley TR, Nivala, J (2012) Are constructed wetlands an appropriate technology for hot, arid climates? In: Proceedings of the 13th IWA Specialized Group Conference on Wetland Systems for Water Pollution Control. Perth, WA, Australia, 25–29 November 2012
16. Masi F (2008) Water reuse and resources recovery: the role of CWs in the Ecosan approach. Desalination 247:28–35
17. Masi F, Rizzo A, Regelsberger M (2018) The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. J Environ Manag 216:275–284
18. Koncagül E, Tran M, Connor R, et al (2017) United nations world water report, facts and figures, wastewater, the Untapped Resource. UNESCO and World Water Assessment Programme

Chapter 5
Constructed Wetlands for Wastewater Management in Egypt: An Overview of 30-Years Experiences in Small/Medium-Size Treatment Plants

Hussein I. Abdel-Shafy, Mohamed A. El-Khateeb, and Mona S. M. Mansour

Abstract Constructed Wetlands (CWs) are well known as an efficient treatment technology for many wastewater sources such as municipal and various industrial effluents. Different engineering designs such as horizontal and vertical flow and hydroponic channels can be implemented according to the required treatment strategies. Greywater and blackwater are also treated in CWs in Egypt and other countries. CWs can achieve high removal rates of various pollutants including total suspended solids, organic pollutants (COD, BOD), nitrogen compounds, phosphates, pathogenic contamination, as well as several heavy metals. There is a wide acceptance and interest in employing CWs due to their advantages such as simple construction, cost-effectiveness, low operation and maintenance cost, high ability to tolerate fluctuations in flow and inlet quality, high pathogens removal, potential for reuse and recycling, aesthetically accepted appearance. Several successfully full and pilot scale CWs are in operation in Egypt as well as in the Middle East and North African countries where the warm climate seems to favour the various CW processes and functions. This chapter presents existing full-scale CWs, hydroponic wetlands, as well as pilot plants using horizontal, vertical, and channel flow for the wastewater treatment in Egypt.

Keywords Constructed wetlands · Hydroponic wetland · Wastewater · Treatment · Water reuse · Pathogens and heavy metals removal · Egypt

H. I. Abdel-Shafy (✉) · M. A. El-Khateeb
Water Research & Polluted Control Department, National Research Centre, Dokki, Cairo, Egypt

M. S. M. Mansour
Analysis & Evaluation Department, Egyptian Petroleum Research Institute, Nasr City, Cairo, Egypt

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_5

5.1 Introduction

Conventional wastewater treatment systems are energy-intensive and include many mechanical components that require high investment as well as high operation and maintenance cost [1], which makes it difficult to use in low-income reasons. On the other hand, constructed wetlands (CWs) have low construction cost, use local materials, very low operation and maintenance cost, minimum energy demand and are simple in operation [1–3], which gives them good prospective to be implemented in developing countries. Furthermore, CWs do not require high skilled engineers to operate; simple labor is enough. Thus, they are accepted as a reliable wastewater treatment technology representing an appropriate solution for the treatment of various types of wastewater [3]. This technology, in fact, acts as a natural-based solution for handling different types of wastewaters [4, 5, 6].

By comparing CWs with conventional wastewater treatment processes, the former have a higher rate of biological performance that enables the conversion of several pollutants into non-toxic by-products or plant nutrients that can be an advantage for water reuse in irrigation [7, 8]. CWs rely upon biological, physical, and chemical processes to remove the contaminants from all types of domestic, sewage and certain industrial wastewaters [9–13]. CWs are capable of removing hazardous pollutants such organic xenobiotics including pesticides, phenolic compounds, dyes, petroleum hydrocarbons, explosives, hormones, and pharmaceuticals [10, 12, 14–18].

CW can be planted with emergent and/or submergent vegetation and may be classified into four types according to their dominant plant species and characteristics [19]: (i) submerged macrophytes (e.g. *Potamogeton crispus*, *Littorella uniflora*), (ii) floating macrophytes (e.g. *Lemna minor*, *Eichhornia crassipes*,), (iii) emerged rooted macrophytes (e.g. *Typha latifolia*, *Phragmites australis*,), and (iv) floating-leaf macrophytes (e.g. *Nymphea alba*, *Potamogeton gramineus*). Another classification in based on their hydrology: (i) horizontal sub-surface flow (HSSF), (ii) vertical subsurface flow (VSSF), (iii) free water-surface (FWS) or surface flow (SF), and (iv) hybrid systems (combination of different designed wetlands) [2, 4, 20–22]. In addition, hydroponic wetlands are designed as isolated declined channels with 1–2% slope, where the inlet flows from the top [23]. For achieving a better removal of nitrogen compounds from wastewater, different designs and types of CW's could be combined as hybrid systems [3, 24].

CWs are receiving an increasing attention as a promising phytotechnology for handling agricultural wastewaters. Studies have shown the efficiency of these system for the treatment of the olive mill wastewater (OMW), fruit processing wastewater, water contaminated with the organic herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid), swine wastewaters (SWW) contaminated with oxytetracycline, winery and distillery wastewater [18, 25–28], among others. In particular, CWs have been successfully employed for the treatment of different sources of wastewaters over the past decades in developing countries under hot and dry or tropical climates [29]. Wastewaters in these countries are characterized by conductivity, productivity, and higher biological activity resulting in higher treatment achievement compared to other countries in the cold climates [30].

5.1.1 Plants in Constructed Wetlands

Vegetation in CWs is an important factor for the efficiency of wastewater treatment. Generally, the common vascular plants in natural wetlands have been used in the CW's, although several ornamental flowering plants found in natural wetlands have also been used. Figure 5.1 illustrates the most common plants used in CWs such as floating aquatic plants, e.g., duckweed (*Lemna*) and water hyacinth (*Eichhornia crassipes*) and vascular plants e.g., common reeds (*Phragmites* spp.) and cattail (*Typha* spp.) These emergent plants grow well in both SF and SSF CWs, where they play an important and vital role in the removal of nutrients. A recent review on 87 CWs in 21 different countries around the world showed that the most common employed ornamental flowering plants are Iris, Canna, Zantedeschian and Heliconia [31].

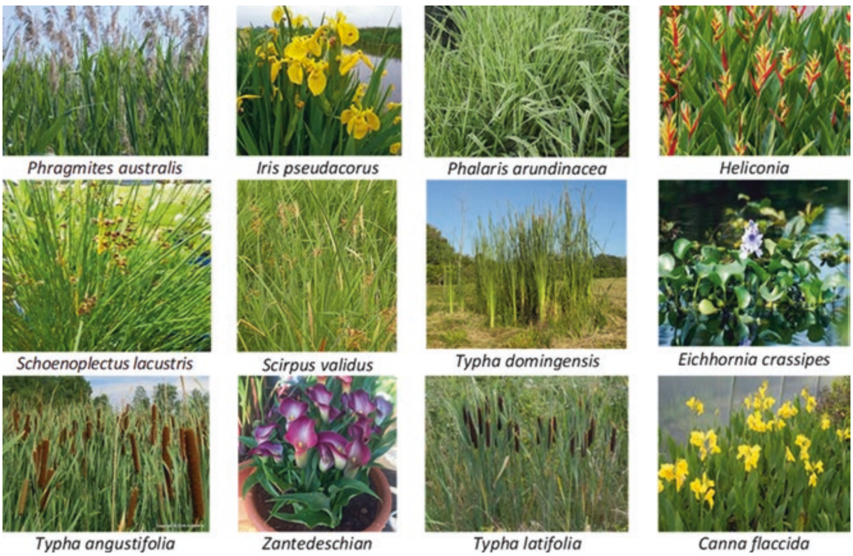


Fig. 5.1 The most common plants that are used in CWs

5.2 Domestic Wastewater in Egypt

5.2.1 Wastewater Production

The annual average collected wastewater during the last 5 years amounts to 6.5 billion m^3 (BCM) [32], corresponding to about 81% of the total annual produced domestic wastewater. It also reported that about 44% of the nationally produced wastewater is not treated, which is equivalent to 2.85 BCM/yr. This huge amount is about 5.1% of Egypt's annual share from the Nile River. There are 358 municipal wastewater treatment plants in Egypt producing 3.65 BCM/yr. treated water. About 0.73 BCM/yr. are primary treated wastewater and the rest of about 2.92 BCM/yr. are secondary treated wastewater [33]. Therefore, the primary and the secondary treated wastewater represent 20% and 80% of the total treated wastewater, respectively. It is worth mentioning that the sewage network has a total length of about 39,000 km. Figure 5.2 presents the future projected collected wastewater capacity through 2030. Moreover, there are three large tertiary treatment plants in Egypt where the sludge is anaerobically digested to produce biogas to compensate for the consumed energy by these treatment plants [33]. The indicator of sanitation access in Egypt is measured by the connectivity of wastewater to the sewerage systems. It complies with the Egyptian Law Number 48/1982 that regulates the protection of the Nile and waterways from any wastewater discharge. As a result, the average sanitation coverage in Egypt is about 50%; 90% in urban areas and only 12% in rural areas.

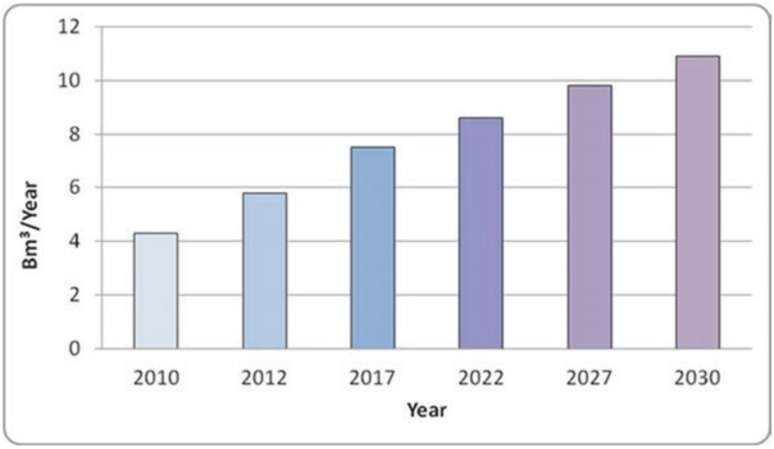


Fig. 5.2 Future projected wastewater collection capacity (BCM) [33]

5.2.2 *Wastewater Reuse in Egypt*

The reuse of treated wastewater is an important strategy to increase the water budget in Egypt as a nonconventional water that should meet the stringent limits and the increasing water demand for non-potable purposes. Guidelines concerning treated wastewater reuse have been developed and issued as Egyptian Code concerning the "Reuse of Treated Wastewater for Agriculture purposes". Treated wastewater can be reused directly in agriculture and/or indirectly for groundwater recharge. An amount of 300 MCM/yr. of treated wastewater is used for agriculture irrigation in Egypt [32, 35–37]. It is very costly to irrigate each hectare of agriculture land. The costs include the networks, seeding, and adjusting land levels, in addition to the cost of the pump stations and generators. Therefore, the average cost for cultivating 1 Feddan (equal to 4200 m^2) is about 10,000 Egyptian pounds (i.e., about $625).

Presently, a reasonable amount of the primary treated wastewater is reused for irrigating of forests trees in the desert of Egypt [32]. Table 5.1 shows a total of 24,000 feddans (about 10,032 hectares) are already cultivated by irrigation with primary treated wastewater, while Table 5.2 presents the types of cultivated plants. However, the total current and potential areas for irrigation with primary treated wastewater in Egypt are 82,000 feddans (34,439 hectares).

Nationally, there are two main essential options for handling the treated wastewater: either direct reuse for agricultural purposes or discharge into the main national agriculture drainage network. Figure 5.2a presents the amount of treated

Table 5.1 Forest areas irrigated by primary treated wastewater in different governorates in Egypt [32]

No	Governorate	Forest	Area (Feddan)	Area (Hectare)
1	Aswan	Elalafy	3000	1260
		Blana	1000	420
2	Sohag	Tahta	1000	420
		Elblyana	1000	420
		Grga	1000	420
		Tma	500	210
3	Bany Swaif	Bandil	265	111.3
		Bayad El-Arab	720	302.4
		East Beny Swaif	900	378
4	Red Sea	Ras Gharib	1000	420
		Safaga	500	210
		El-Qasir	500	210
5	Qena	Naga Hammadi	2000	840
		Farshot	1500	630
		Qena	3000	1260
6	Menya	Menya El-Gededa	5000	2100
		Samalot	1000	420
Total			23,885	10,031.5

Table 5.2 Types of cultivated plants irrigated with primary treated wastewater in different governorates in Egypt [32]

Governorate	Cultivated plants
Aswan	Jatrova, Kaya, J ujoba
Luxur	Sysaban, Jatrova, Kaya, Jujoba
Qena	Sysaban, Jatrova, Kaya, Jujoba
Sohag	Sysaban, Jatrova, Kaya, Jujoba
Asuitt	Casuarina, camphor
Beny Swait	Casuarina, camphor
Red Sea	Casuarina,
Matroh	Casuarina, camphor, Jatrova
North Sinai	Ornamental palm, casuarina, camphor
South Sinai	Kaya, casuarina
Monofia	Kaya, casuarina
Lsmaliia	Casuarina, camphor

wastewater discharged to the main drainage network and Fig. 5.2b the amount reused directly for agricultural purposes in different Egyptian governorates in 2011 [38] (Fig. 5.3).

5.3 Constructed Wetlands in Egypt

5.3.1 Lake Manzala CW Project

In Egypt, there are two major concerns: environmental and economic problems related to the poor quality of north flowing agriculture drainage waters mossed wit sewage water. In January 2001, the construction of the CW facility began on a 100-hectare area South-West of Port Said City, Egypt, one of the most poorly served areas in Egypt where local residents have no access to clean potable water, electricity, sanitation, as well as any other basic services.

The project was a cooperative effort between the Global Environmental Facility (GEF), the United Nations Development Program (UNDP), and the Egyptian Environmental Affairs Agency (EEAA). The CW was designed to treat 25,000–50,000 m^3/day of polluted drainage water from the Bahr-El-Baqar drain to improve the water quality in Lake Manzala that is connected to the Mediterranean Sea. Lake Manzala is located in the North-Eastern edge of the Nile Delta (Fig. 5.4). The Egyptian authorities were concerned over the discharged drainage water to Manzala Lake as a major environmental and economic problem. Such drainage waters are heavily polluted wastewater crossing the Nile Delta and enter large coastal lakes before discharging into the Mediterranean Sea. The resulting environmental contamination of the Mediterranean Sea coastal area violates the international agreements, signed by Egypt, including Barcelona Convention.

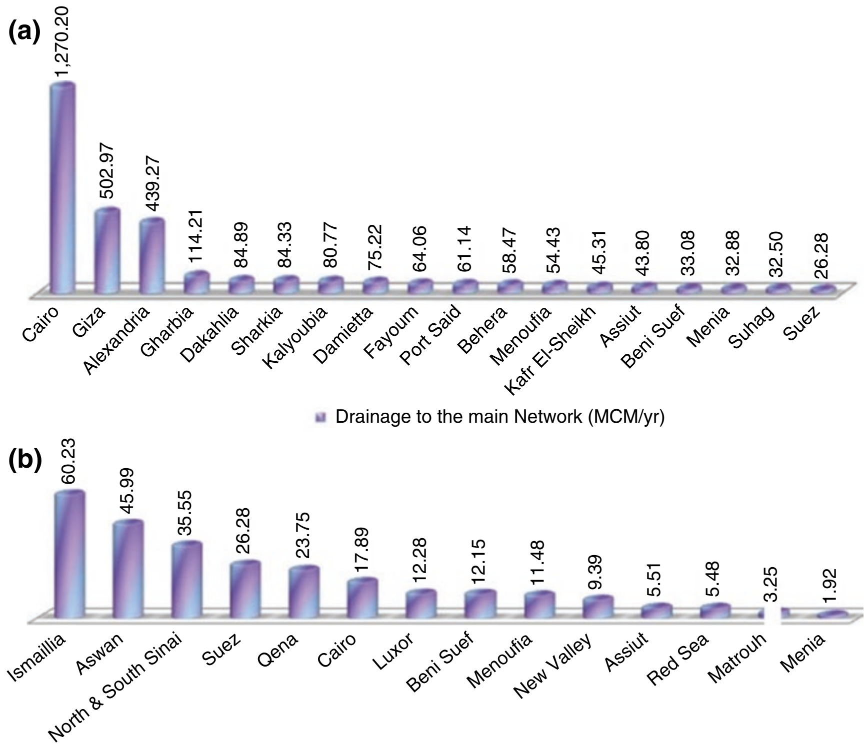


Fig. 5.3 (**a**) Discharge (MCM/Year) to the main drainage network, and (**b**) direct reuse (MCM/Year) of treated wastewater in Egyptian Governorates [32]

The facility includes intake screw pumps, surface treatment cells, sedimentation basins, subsurface reciprocating cells, fish rearing facility, pilot test cells, and the treated effluent reuse area. The 5 years demonstration project included 3 years for design and construction followed by 2 years of operation to demonstrate the performance, and optimize the implemented CW systems in Egypt. Within the CW facilities, the project includes a commercial scale of 60 feddans (25 hectares) for a fish farm, using the treated water for the purpose of compensating the plant operational costs. The long-term aim is to implement the innovative, and low-cost wastewater treatment technologies in the area and the region.

The total area of the lake is 250,000 feddans (104,207 hectares) and the inflow to the lake is 4 BCM/year of polluted water. Bahr El-Baker drain contributes with about 25% to the total lake inflow, which is mainly agriculture drainage water mixed with sewage water. The area of the CW is 200 f (83 hectares) (Fig. 5.5), i.e., about 1% of the total Lake area (Fig. 5.4). It receives the highly polluted water from many drains especially Bahr El-Baqr drain. Therefore, low dissolved oxygen was detected, aquatic bio-diversity declined, fish, produced by the lake or fish farms in the area were not suitable for human consumption. The pollution load of Lake namely BOD, TSS, total nitrogen, and total phosphates were 40, 160, 12, and 4 mg/L, respectively.

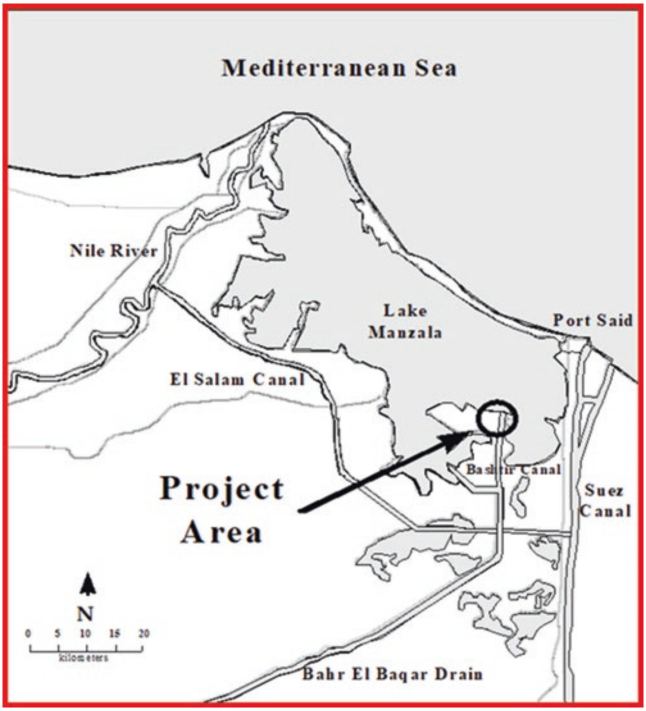


Fig. 5.4 Location of Lake Manzala at North-Eastern edge of the Nile Delta

Fig. 5.5 The 83 hectares CW at the Lake Manzala

This CW project has proved that adequate treatment can be attained and safe reuse at a wide range for non-potable purposes particularly for fish farming. It also helped to make Egypt a regional leader in CWs and self-sufficient in the reuse of innovative wastewater treatment technologies. The key advantages of the project are:

- It examined various technological processes onsite for the purpose of optimising the treatment efficiency, including various CW designs and different wastewater strengths.
- Further study will be carried out to determine the optimum treatment efficiency of the CW for handling higher flow rates, with stronger wastewater of higher pollutant loadings from the fish farm effluent. More work is considered to determine the most convenient wetland plant species that can be used effectively in the highly saline water.
- It will support the local community through education, training, and marketing of their bio-products.

Although successful, the CW project is unable to achieve broader environmental as well as economic goals. Achievement of these goals has not been reached due to a number of constraints related to project design and implementation. Overall, this CW offers a very useful model to investigate and to learn from for any future projects concerning the construction of an efficient, innovative, and low-cost wastewater treatment technology.

5.3.2 Gravel Bed Hydroponic Wetland for Municipal Wastewater Treatment in Ismailia

This system treats sewage water through a field-scale gravel bed hydroponic wetland (GBHW) in a remote area under the sub-tropical climate of Egypt at Abu-Attwa village [23]. In the previous times, the wastewater of this village and its surroundings was discharged to the nearby Temsah Lake. As a result, the lake became contaminated, aquatic plants were flourished, unpleasant smell existed, and nutrients and water of the sewage were lost. The GBHW has been implemented as secondary treatment process at this area. The treatment system consisted of two GBHW stages in series (Fig. 5.6a). Each stage consisted of six parallel channels. Each of the first stage channels was 120 m long, 2 m wide, and 0.5 m deep at 1% slope. They were planted with *Phragmites australis* (elephant grass). Each of the second stage channels was 50 m long, 2 m wide, 0.5 m deep at 1% slope, and were planted with *Cyperus papyrus* (Cyperaceae family) (Fig. 5.6b). The later plant is very common in Egypt and other countries [53]; it was used by the ancient Egyptians for manufacturing of papyrus paper.

The raw municipal wastewater was primary treated in sedimentation-settling basins followed by a trickling filter. The effluent was directed to the GBH wetland

Fig. 5.6 (**a**) The second stage of the GBH treatment system in Ismailia, Egypt [23] and (**b**) *Cyperus papyrus* of the Cyperaceae family

system where the flow rate was 20 L/min to each channel through the first stage, and the effluents were directed simultaneously to the second stage by gravity. The total daily treated wastewater volume was 100 m^3/d. The GBHW channels have been operated intermittently throughout the study period; the flow of wastewater was only 18 hr./day. The purpose was to provide sufficient period of time for the channels to dry and to allow atmospheric air to diffuse into the plant root zone. The physical, chemical and bacteriological characteristics of the sewage influent and effluent were studied for a period of 12 months. The removal rate of BOD_5, Total Suspended Solids (TSS) and Ammonium-Nitrogen (NH_4-N) ranged from 70.3% to 93.2%. Effective removal was also achieved for pathogenic bacteria and microorganisms. The overall results indicated that the GBH as a CW is capable of handling the municipal wastewater in Egypt up to the acceptable environmental level suitable for recycling in agriculture as an important process in arid and semi-arid areas [23].

5.3.3 Decentralized Wastewater Treatment in Sinai via Gravel Bed Hydroponics Wetlands

This GBHW was designed and implemented for municipal wastewater in Sinai Peninsula, Egypt, to serve a large village and the surrounding areas [39]. These areas have no industrial activities; therefore, the concerned municipal wastewaters (1270 m^3/d) were not mixed with any industrial discharge. The treatment system consisted of the main piping systems to transfer the wastewater to the treatment site. The inlet is subjected to three screening, followed by grit chambers (3×1.5×2.5 m each), followed by sedimentation basins. Each screening system dimensions are 1.5×2.0 m. The outlets of theses chambers are subjected to the distribution system through 6 valves. Each valve distributes the wastewater into two GBH channels.

The wastewater flows by gravity to 6 receiving small shallow basins controlled by giant valves. Each of these basins was split into two GBHW channels. Therefore, there is a total of 12 GBH channels. The dimension of each channel is 2.0 m width, 100 m length and 0.45 m depth. The slope of each channel is 2% to allow the flow of wastewater by gravity up to the end of the treatment channels. All channels were filled with gravel as a media for treatment and filtration (Fig. 5.7a) and planted with vascular plants, namely *Phragmittes australis* (Elephant grass). These plants grow in the Egyptian climate up to 3–4 m height. The treated effluents were allowed to flow further to a maturation pond (dimension of 50*20 m) at the depth of 2.0 m (Fig. 5.7b). The final treated effluent is reused for irrigating eucalyptus trees on the sandy soil of Sinai. However, other plants were also examined.

The results of this investigation (Table 5.3) indicated that the GBHW is very efficient in the removal of COD, BOD, TSS, TKN and the total phosphates (TP) with respective removal rates of 68.3%, 74.7%, 76.9%, 42.9% and 47.5% [39]. Further improvement was reached by the maturation pond where the removal of COD and BOD were 66.3% and 69.8%, respectively (Table 5.3). The overall removal of COD, BOD, TSS, TKN and TP was 89.4%, 93.2%, 98.0%, 71.4% and 62.5% respectively (Table 5.3).

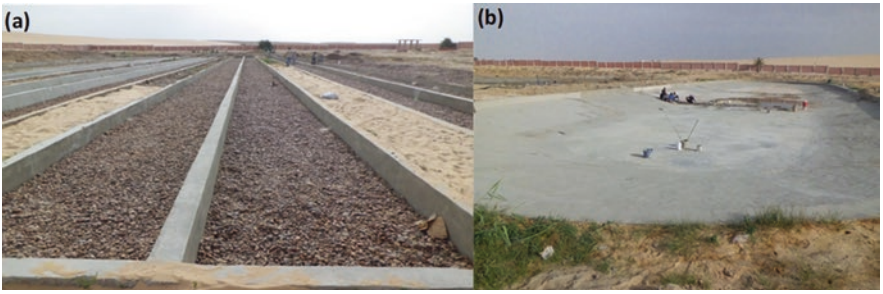


Fig. 5.7 (**a**) The 12 GBHW channels; each channel is 100 m long, 2.0 wide and 0.5 m deep, filled with flint of radius size from 2 to 2.7 mm, (**b**) maturation pond after construction

Table 5.3 Treatment of sewage water by GBHW followed by maturation pond in Sinai [39]

Parameter	Unit	Raw Sewage[a]	GBHW Effluent		Maturation pond Effluent		Overall (%)
			Conc	%	Conc	%	
TDS	μmhos	1377	1197	13.1	860	28.2	37.5
EC	mg/L	2311	2088	9.6	1644	21.3	28.9
COD	mg/L	857	271	68.4	91	66.4	89.4
BOD	mg/L	672	162	75.9	45.7	71.8	93.2
TSS	mg/L	390	90	76.9	75	16.7	98.0
TKN	mg/L	70	40	42.9	35	12.5	71.4
TP	mg/L	8.0	4.2	47.5	3.8	9.5	62.5

[a] After sedimentation

By correlating these results with the permissible Egyptian regulations [40], it was concluded that the final treated effluent can be safely reused for irrigation with regards to Class 2 (secondary treated water), in this case for irrigation of woody trees as an economical value. The latter is an environmentally friendly option, particularly in an area like Sinai Peninsula. In addition, the results indicated that there are no hygienic risks. This is mainly due to the long HRT in the CWs as well the maturation pond as passively affected by the sunlight that are very effective in the removal of fecal coliforms from the studied wastewater.

5.3.4 Cilioprotists as Biological and Pollution Indicators of GBHW Efficiency

A GBHW was constructed and implemented for sewage treatment in several Egyptian villages, where they provided an excellent environment for a very wide range of the ciliates species “Cilioprotists” (23 species). These organisms were very useful to study the biological system of the GBHW. They can be employed as good indicators for various saprobic conditions. In addition, these ciliates provided an excellent means to estimate the efficiency of the GBHW system for sewage treatment. The obtained results confirmed the ability of the GBHW in producing a high-quality treated effluent with excellent microbial reduction that meets the quality standards for reuse in irrigation according the local and the international regulations [41].

5.3.5 Hydroponic Rooftop Gardens in Informally Developed Areas in Egypt

This work investigated the development of the rooftop farming through a hydroponic system for the purpose of improving the quality of life for the majority of residents. The study aimed to explore the advantages and the potentials of green vegetative rooftops [42]. Rooftop gardens are presented mainly as a podium for urban farming [6]. The general main aim is solving social, environmental, as well as the economic problems in large cities like Cairo with a hot arid climate as well as in different developing countries. The investigation was based on extensive local studies that address such green-roof hydroponic in an arid climate. A long-term strategy of adopting roof farming could certainly support the sustainability for food security, as well as the addition of social, environmental and aesthetical advantages to cultivated areas.

Appropriate knowledge is required for implementing the hydroponic roof gardens in Egypt. The study showed that they are cost-effective, simple to design and to implement. Nevertheless, the important factors are: the construction restrictions and the climatic conditions, beside the social factors. The present application had great success as well as environmental and social benefits. However, a number of challenges that hinder the spreading of such hydroponic technology in Egypt including legal encouraging support to private sector in participating in these valuable projects. By overcoming such challenges, a reasonable ratio of environmentally friendly green areas can be reached in the near future at ratio of 4 m^2/pe [43].

5.3.6 *Constructed Wetland in a Remote Area for Greywater Treatment*

The study area is east of Sharquiya Governorate, 55 km NE of Cairo. Fifty years ago, this area was a desert without any agriculture activity. It is now a well-known organic farm that depends on groundwater and rain for irrigating the purely organic and pharmaceutical plants. The overall purpose was to reuse the treated wastewater, recycling the nutrients, and protecting the environment and the public health. The work was designed to implement integrated models of wastewater treatment and reuse [44].

A full-scale CW was established in this farm for greywater treatment and reuse of treated effluent to irrigate lumber trees. The greywater originated from children and boarding school, training workshops, offices, laundry, kitchen and few houses. The raw greywater characteristics were within the average strength in Egypt. The CW was designed for the treatment of 20 m^3/d. The greywater was primary treated in a three-chamber sedimentation/septic tank of 56 m^3 capacity (Fig. 5.8a) followed by a SSFCW of 200 m^2 area (Fig. 5.8b). The HRT for the septic tanks and the CW were 6, and 7 days, respectively.

The results showed that COD and BOD were eliminated by 87% and 89%, respectively. The fecal coliform count was also reduced by 5 log units. The physico-chemical characteristics of the treated wastewater were within the permissible limits of the Egyptian standards for irrigation [40] Meanwhile, no odor problems or

Fig. 5.8 (**a**) Construction of the septic tank, (**b**) Constructed wetlands before planting in Sharquiya

insects existed due to employing the SSFCW. Employing the proper engineering design of a CW and efficient primary treatment process has improved the quality of the treated effluent. The treated water was reused onsite for irrigating the lumber forest trees on the local sandy soil. The advantages are soil quality improvement, recycling nutrients, higher agricultural production and groundwater protection. Treated water reuse could save about 10 m^3/d of fresh water that were consumed for irrigating the lumber trees [44]. The CW system can achieve good performance all year around due to the sunny and moderate climate in Egypt. It was, therefore, concluded that CWs are simple, low-cost, and efficient treatment systems particularly appropriate for decentralized and remote areas in Egypt [44].

5.3.7 Greywater Treatment Using Different Designs of Gravel or Sand Bed Hydroponic Filters

Different designs of sand bed hydroponic filter as a secondary treatment for a primary treated greywater effluent were studied in order to optimize the treatment efficiency. The following hydroponic filters were examined: (1) Gravel bed filter down flow (GFDF), (2) gravel bed filter up flow (GFUF), (3) sand bed filter down flow (SFDF), (4) gravel bed filter followed by sand bed filter (GFSF), and (5) a horizontal flow sand bed filter (HFSF). The pilot plants were designed and implemented at the National Research Center of Egypt.

During the period of this study, the GFDF, GFUF, and SFDF were examined with a wastewater influent flow rate of 173 $m^3/m^2/d$, while the GFSF and HFSF were examined at a flow rate of 86.5 $m^3/m^2/d$ [45]. The operation and dimensions of the designed hydroponic filters are given in Table 5.4. The raw greywater characteristics varied greatly from 319.6–491 mg/L for COD, 120–307 mg/L for BOD_5, and 26–201 mg/L for TSS. The biodegradability (BOD_5/COD) was 0.54, slightly lower than the average domestic wastewater. This confirms that the greywater contains non-biodegradable organic contents, particularly in dissolved forms. This greywater

Table 5.4 Design and operating parameters for the different GBHF and SBHF systems [45]

System	Area (m^2)	Depth (m)	Type and size (mm) of media	HLR** (m^3/m^2/day)	OLR** (g BOD/m^2/day)
Gravel bed hydroponic filter down flow (GFDF)	1.0	1	Gravel of 2–4 mm	173	18.3
Gravel bed hydroponic filter up flow (GFUF)	1.0	1	Gravel of 2–4 mm	173	18.3
Sand bed hydroponic filter down flow (SFDF)	1.0	1	Sand of 1–2 mm	173	33.9
Gravel filter followed by sand filter (GFSF)	2	03	Sand of 1–2 mm and gravel of 2–4 mm	86.5	9.3
Rough filter (HFSF)	2	03	Gravel of 2–4 mm	86.5	23.8

**OLR = Organic Loading Rate

was treated first by sedimentation as primary treatment followed by the different hydroponic filter systems. The only difference between downflow and upflow GBHF is the direction of wastewater feeding. Table 5.4 shows the design and operation parameters of these filters.

The COD of GFSF and HFSF effluent was lower than that the GFDF, GFUF, and SFDF systems. This may be attributed to the lower HRT applied to the GFSF and HFSF compared to the other systems (namely, GFDF, GFUF and SFDF). BOD_5 removal in the GFSF and HFSF systems was 82% and 81.2%, respectively. The level of detergents was also reduced in the effluent. The hydraulic loading rate (HLR) was controlled at 86 $L/m^2/d$ and the organic loading rate (OLR) was 23.7 g $BOD_5/m^2/d$.

For the treated effluent of the GFSF, the residual concentration of BOD**5**, COD, and TSS was 16 mg/L, 43 mg/L, and 7.5 mg/L, respectively. The corresponding concentration in the HFSF effluent was 17, 40, and 9 mg/L. It was, therefore, found that the physico-chemical characteristics of the treated effluent of both GFSF and HFSF complied with the National Regulatory Standards of the treated wastewater reuse in agriculture irrigation [40].

From these results, it was concluded that the designed gravel or sand bed hydroponic filter, such as the GFSF or HFSF, for greywater treatment is a promising system providing a treated effluent that can be reused for agriculture irrigation. Sand and/or gravel filters can be used for a broad range of applications, including single-family residences, small communities, and large commercial establishments due to the fact that these are low-cost and simple techniques.

5.3.8 Integration of UASB and Two Different CWs

The enhancement of treated effluent quality via CW systems is increasingly employed in different countries throughout the world. For this purpose, a pilot plant study focused on two treatment schemes for sewage water [46]: an Up-flow Anaerobic Sludge Blanket (UASB) reactor followed by SSF and/or SF CWs (Fig. 5.9). The common vascular macrophytes in Egypt, namely *Typha latifolia* (cattail), was used at a planting density of a three rhizomes/m^2. To evaluate the role of such vascular plants in the pilot CW, two unplanted gravel beds were used; one identical to the SSF unit and the other identical to FWF unit operated as the control ones.

During the 12 months study period, all wetlands were fed with the UASB effluent at an OLR ranging from 17.3–46.8 kg BOD_5/ha/d (55.1–134.6 kg COD/ha/d). The obtained results revealed that the level of COD and TSS in the treated effluent of the SSF was lower than that of the FWS. The overall performance of the SSFCW demonstrated much higher removal rates of the studied pollutants than the unplanted CWs. The FC elimination reached 4 log units [46].

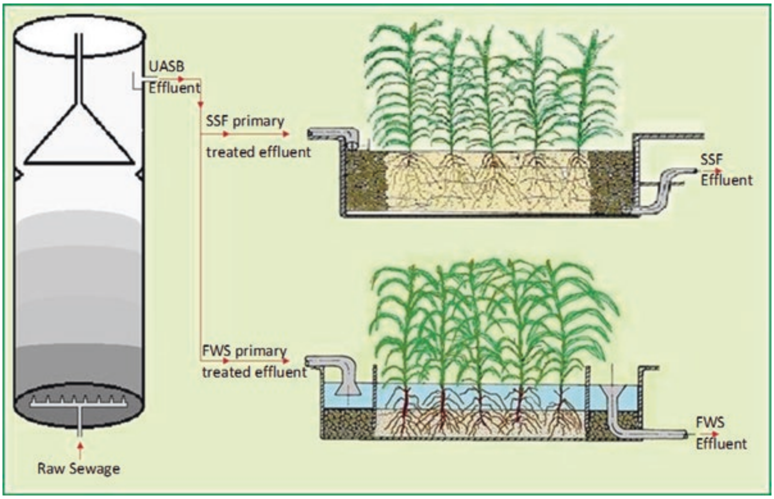


Fig. 5.9 UASB reactor followed by SSF and FWS CWs

5.3.9 Sewage Water Treatment by UASB Followed by CWs

A further study was carried out on the feasibility of employing the up-flow anaerobic sludge blanket (UASB) reactor followed by SSFCWs in a pilot plant for the treatment of sewage. The obtained results showed that the UASB reactor (as a primary treatment step) removed 67.7, 71.4 and 65.5% of COD, BOD and TSS, respectively, with corresponding residual concentration of 197, 120 and 79.3 mg/L. The count of Fecal Coliform was reduced by 1–2 log units in all cases. The residual count reached 1.6×10^6 MPN/100 mL.

This anaerobically treated wastewater effluent was subjected to the SSFCW. The later was highly efficient in the removal of COD, BOD and TSS with residual concentrations of 56.7 mg/L, 20.6 mg/L and 5 mg/L, respectively. Fecal coliforms were greatly reduced to $1.1\text{x}10^3$ MPN/100 mL. The quality of the obtained treated effluent complied with the National Regulatory Standards for agriculture irrigation [40]. Therefore, it was concluded that the combination of anaerobic UASB with the SSFCW is an effective treatment system for handling the sewage [47].

5.3.10 Blackwater and Greywater Treatment in UASB Followed by CW

Municipal sewage water separation into greywater and blackwater proved to be very effective strategy preventing the contamination of greywater by eliminating the fecal source, thus reducing the cost of wastewater treatment. The UASB reactor is known as a cost-effective system for organic wastewater, while CWs offer a

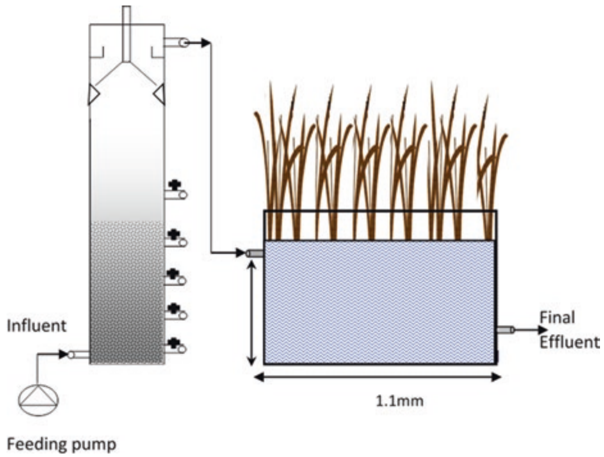


Fig. 5.10 Schematic diagram of the pilot system: UASB followed by HSSFCW [48]

low-cost treatment solution in developed and developing countries, particularly in semi-arid and arid areas. In this study, two separate UASB reactors were used as primary treatment step followed by CWs for the separate treatment of greywater and blackwater separately (Fig. 5.10). The HRT in the UASB was 24 and 6 h for the two reactors, while the OLR were 1.16 and 1.88 kg/m^3/day for the treatment of greywater and blackwater, respectively. The COD removal rate of in the UASB was 60% for greywater and 68% for blackwater. Further quality improvement was reached after the application of the HSSFCW. The overall removal rates for COD, BOD_5 and TSS was 87.7%, 89.5% and 94% for greywater and 94.2%, 95.6% and 94.9% for blackwater, respectively. Therefore, it was concluded that the integration of UASB and CWs is a promising technology for the treatment and reuse of blackwater and greywater, particularly in the arid and semi-arid areas [48].

5.3.11 Investigation of the CW Inlet Area Shape

The purpose of this study was to investigate the effect of two different shapes of the CW inlet. Four pilot-scale units were constructed and operated under a 2-days HRT in parallel in continuous feeding experiments. The treatment system consisted of a filtration unit followed by two CW units: one FWS and one SSF (Fig. 5.11). Two different shapes of the inlet works were tested per design: rectangle and triangle. The results indicated that the triangle-shaped inlet showed a higher removal of COD (73%), BOD_5 (83%), TSS (81%), fecal coliform (effluent: 104 MPN/100 ml), fecal streptococci (effluent: 103 MPN/100 ml), *pseudomonas aeruginosa* (effluent: 102 MPN/100 ml) and *Salmonellae* (100%). The removal rates in the FWS unit were slightly higher than the SSFCW unit in terms of COD and BOD. It was concluded that the inlet design has a slight effect on the CW efficiency (Kamel et al. 2010)

[40]. Therefore, the authors suggested that the well-designed inlet shape has a considerable effect on the efficiency of CW [49].

5.3.12 *Agriculture Drainage Water Treatment in FWS CW Followed by Floating Aquatic Plant CW*

The treatment of agriculture drainage water by two CW types has been studied in Egypt for the purpose of enhancing the treated water quality. The treatment scheme consisted of FWS CWs followed by floating aquatic plant (FAP) CWs (Fig. 5.12). In the FWSCW, *Typha latifolia* (cattail) was used as the macrophyte and water hyacinths in the FAP. The results showed that this combined treatment system was efficient in the removal of TSS, COD, BOD, ammonia and phosphates. The concentration of COD, BOD, TSS, ammonium compounds and phosphates was reduced from 115.2, 71.4, 79.4, 4.7 and 1.4 mg/L to 41.8, 13.9, 13.5, 1.8 and 0.5 mg/L, respectively. In all cases, the treated effluent complied with the National regulatory standards for reuse of wastewater treated effluent [50], demonstrating that the CW system is an efficient treatment system for agriculture drainage water [51].

Fig. 5.11 CW pilot units with different inlet shape designs [49]

Fig. 5.12 Combined system of FWS and FAP CWs for drainage water treatment; (**a**) FWS and (**b**) FAP units [51]

5.3.13 Combination of Sedimentation Process and CWs

The efficiency of two field-scale HSSF CWs was studied for the treatment of agriculture drainage water. One system was planted with three different plants (*Canna*, *Phragmites australis* and *Cyperus papyrus*) and the other was unplanted as a control (Fig. 5.13). The surface area of each CW was 654 m^2, the flow rate 20 m^3/d and the OLR ranged between 1.7–3.4 kg BOD_5/m^2/d, while the HRT was 11 days [52].

The results indicated that the planted HSSFCW had better removal rates for COD (88%), BOD_5 (91%), TSS (92%), and phosphates (60%). Furthermore, 4 logs of total coliform were eliminated from the wastewater in the planted CW compared to 3 logs in the unplanted. In the planted unit, the nutrient uptake by the plant species reached 29, 30.9 and 38.9 g P/m^2 and 63.1, 49.46 and 82.33 g N/m^2 for *Canna*, *Phragmites* and *Cyperus*, respectively. This indicated that *Cyperus papyrus* plant is capable for a higher phosphate and nitrogen uptake than the other studied plants. Moreover, a higher removal of microbiological parameters was reached in the planted CW compared to the unplanted one. Most plants in the CWs survived over the 12-month experimental period. These findings indicated the positive role of the vascular plants in bacterial removal from wastewater [53, 54]. The overall performance by the different vascular plants indicated that *Cyperus* species is suitable for CW due to its high ability for nutrients uptake and pathogens elimination. The unplanted CW exhibited a reasonable removal of COD, BOD_5 and TSS, but the removal of pathogens and nutrient elements was low. After disinfection, the reclaimed water could be recycled for the purpose of non-restricted irrigation according to the Egyptian Holding Code Standards for wastewater reuse in agriculture [39]. It was concluded that the use of HFCW planted with *Canna*, *Phragmites*

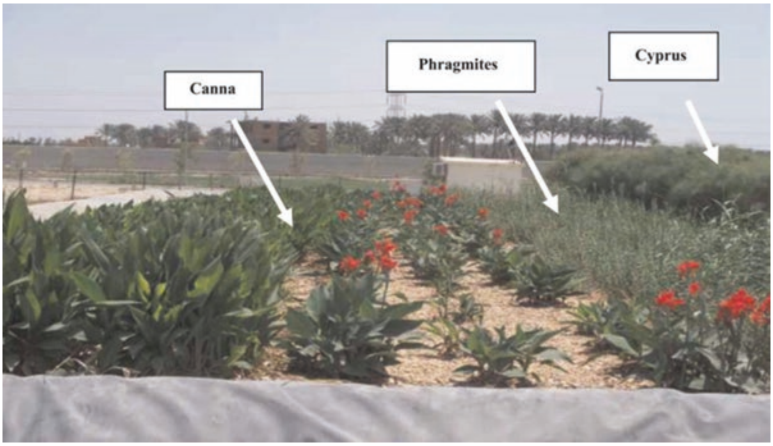


Fig. 5.13 Field-scale CW units planted with different plant species agriculture drainage treatment [52]

australis and/or *Cyperus* plants proved to be efficient in the treatment of this polluted water [52].

5.3.14 Combination of UASB and Hybrid CW for Sewage Treatment

The integration of an up-flow anaerobic sludge blanket (UASB) reactor followed by a hybrid CW system (FWS and SSF) has been investigated for the treatment of sewage in a pilot study (Fig. 5.14). Both CWs were planted with *Typha latifolia*, a common macrophyte in Egypt, at a planting density of three rhizomes/m^2. The CWs were continuously fed with the treated UASB effluent. During the study period, the OLR ranged between 41.4–74.5 kg BOD_5/ha/day and 84.5–152 kg COD/ha/day. The efficiency of this integrated system was high, resulting in effluent concentrations of 2.6, 6.4, and 21.4 mg/L for TSS, BOD, and COD, respectively. In addition, significant removal of the microbiological contaminants (total coliform, fecal coliform, fecal streptococci, *P. aeruginosa*, *Salmonellae*, total *Staphylococci*, and *Listeria monocytogenes*) was found [55].

5.3.15 Combination of Sedimentation Process and a Hybrid CWs for Blackwater Treatment

A further investigation was carried out on the efficiency of hybrid CWs for concentrated blackwater treatment [24] at pilot-scale. A pilot system was tested comprising a screening/sedimentation process as primary treatment, followed by a hybrid CW (HSSF and VFCW) (Fig. 5.15).

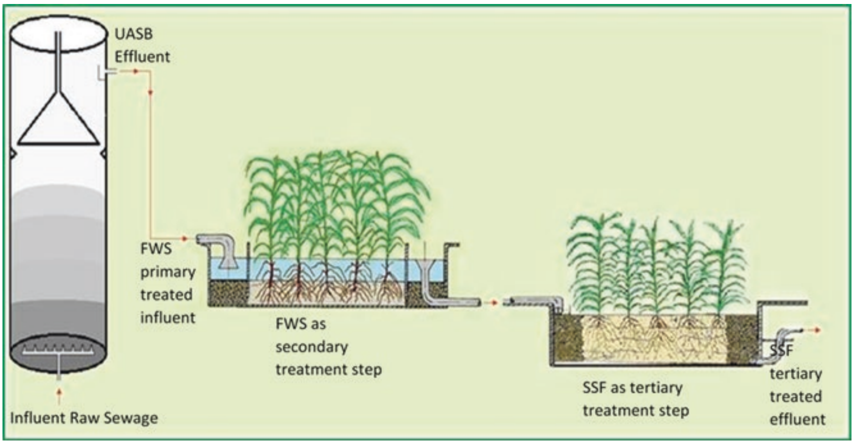


Fig. 5.14 A pilot UASB reactor followed by a hybrid CW system (FWS and HSSF) [55]

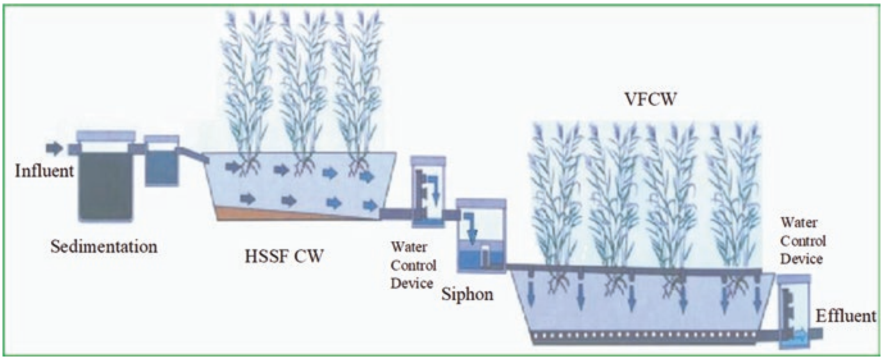


Fig. 5.15 Schematic diagram of the hybrid HSSF and VFCW for blackwater treatment [24]

The results showed that the sedimentation process was able to remove about 64.8%, 58.0%, and 56.8% of BOD_5, COD, and TSS, respectively. After the HSSF CW, the removal rates of BOD_5, COD, and TSS increased to 88.0%, 87.1%, and 82.9%, respectively. The overall removal (after the last VFCW stage) reached 98.0%, 98.5%, and 97.4%, for BOD_5, COD, and TSS, respectively. This, the final effluent complied with the National Regulatory Standards for unrestricted water reuse. This study showed that the hybrid CW represents a cost-effective technology for wastewater treatment that can be highly efficient in the climate of Middle East, Africa, i.e., in arid, and semi-arid areas. The hybrid CW enhanced the effluent quality, mainly due to the relatively low flow rate and the larger surface area. Such CWs act as gravel filters, thus, providing further sedimentation of the suspended solids as well as adsorption on the biofilm adhered to both the gravel and the plant roots. The combination of HSSF CW followed by VFCW proved to be a promising integrated system for the treatment of such strong blackwater. Such hybrid CWs can handle high hydraulic and organic wastewater loads [8, 24], as it has been proved in other cases under arid climates [56, 57].

5.3.16 Enhancement of Degreasing/Settling Tank Followed by CW for Greywater Treatment

Treated greywater can be reused for non-potable purposes such as landscape irrigation and toilet flushing. In this study, greywater was collected from five flats and connected to a pilot plant to examine different treatment processes for treatment and safe reuse of the treated water. The treatment system consisted of sedimentation/settling tank followed by a HSSF and VFCW (Fig. 5.16) [58]. To enhance the sedimentation tank, the "Effective Micro-organism (EM)" was added. The effect was examined firstly in "jar test" batch experiments to determine the optimum operating conditions. The experimental work involved monitoring of physico-chemical

Fig. 5.16 A pilot plant comprising of a sedimentation tank followed by a hybrid CW (HSSF and VFCW) for greywater treatment [58]

Table 5.5 Design and operation parameters of the hybrid CW treating greywater [58]

Dimensions and materials	
No. of units	2
Length	1.2 m
Width	1.0 m
Water depth	0.50 m
Plant	*Phragmittes austeralis*
No. of rhizomes/m^2	3
Substrate	Sand (0.20 ~ 0.45) mm, Rice straw (15 kg/m^3), and small gravel (0.50 ~ 1.00) mm
Metal piping inlet and outlet	PVC
Release and retain greywater	Valve
Operating conditions	
Hydraulic retention time (HRT)	2.2 d
Organic loading rate (OLR)	270.91 kg BOD/ha/d 356.36 kg COD ha/d

characteristics of greywater under varying operating conditions at different sedimentation periods. The design and operating conditions of this treatment system using the hybrid CW are given in Table 5.5.

The overall results showed that the addition of 1.5 ml/L of EM to the raw greywater in the settling tanks followed by 3.0 hr. retention resulted in remarkable removal of TSS, COD, BOD_5 and oil & grease at corresponding rates of 78%, 70%, 83%, and 89%. When this primary treated greywater was subjected to the hybrid CW, the removal rates reached 73%, 65%, 63%, and 84% for TSS, COD, BOD_5 and oil & grease, respectively. Overall, the combined system reached 94%, 90%, 94%, and 98% removal of TSS, COD, BOD_5 and oil & grease, respectively [58]. *E. Coli* count and the number of cells or eggs of Nimatoda reached 100/mL and "1 Count/L", respectively in the outflow. The characteristics of the treated effluent were within the limits for unrestricted reuse according to the "Egyptian regulation, 2005" [50].

5.4 Role of CWs in Heavy Metals Removal

5.4.1 Gravel Bed Hydroponic Wetland

An experimental study was conducted for a period of 9 months on a gravel bed hydroponic wetland (GBHW) using artificially contaminated municipal wastewater by 5 different heavy metals. The metals were Cd, Cu, Ni, Pb, and Zn at a concentration of 5.0 mg/L each [59]. The dimensions of the GBHW were 30.5 m length, 0.6 m width, 1.2 m depth, and slope 2% (Fig. 5.17). The GBHW was planted with *Phragmites australis*. The study revealed that metals were greatly eliminated between 72% for Cd to 89% for Cu and Zn. Metals were mostly adhered to the solids that were precipitated between the gravel media of the GBHW. The reeds also contributed to such an elimination. The plant roots were the highest and the stems were the lowest in accumulating the studied metals. The distribution of metals in the plant was: roots > leaves > stems [59]. These results were also confirmed by other investigators, who studied similar GBHW with the same dimensions [60].

5.4.2 Fate of Heavy Metals in CWs for Greywater Treatment

A similar study was conducted to evaluate the fate of heavy metals in SSFCWs treating real greywater [61] (Fig. 5.18). The CW was planted with two different vascular aquatic plants; *Phragmites australis* and *Schoeneplectus lacustris*. Greywater was first applied to an Imhoff tank to remove the suspended solids, and

Fig. 5.17 A pilot gravel bed hydroponic wetland at 2% slope tested for heavy metals removal from wastewater [58]

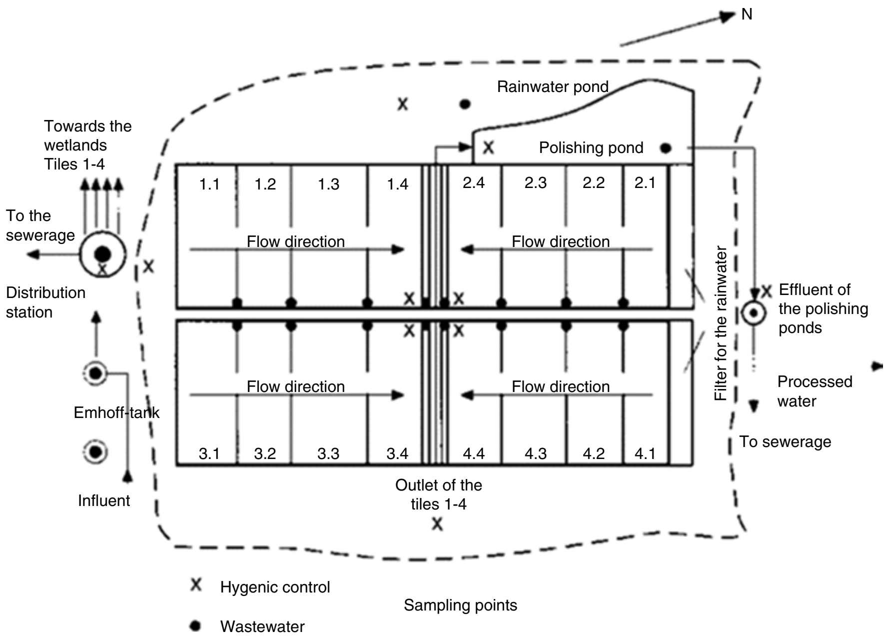


Fig. 5.18 Pilot SSFCWs for the treatment of greywater [61]

the effluent was directed to a CW. The CW effluent was then directed to a polishing pond.

The studied metals were Cr, Cu, Fe, Cd, Ni, Zn, and Pb. The translocation of these metals in the two plant roots, stems and leaves was also measured. The results showed that *P. australis* had a higher tendency to uptake metals than *S. Lacustris*. The level of metals was much higher in the roots, followed by leaves and stems. However, metals were concentrated mostly in the sludge than in the plants. Metals concentration was in the following order: Fe > Zn > Cu > Ni > Pb > Cd > Cr. The presence of such metals was attributed to the household greywater, therefore, iron and zinc both were enriched to a higher extent than the other ones. It was also confirmed that the level of studied metals in vascular plants grown in the CW were higher than in those grown in the "controlled" plant area.

Metal removal rates in CWs depend also on the type of element (Hg > Mn > Fe ¼ Cd > Pb ¼ Cr > Zn ¼ Cu > Al > Ni > As), as well as substrate conditions, metal ionic forms, season, and plant species [62]. It was found that the accumulation of metals in the greywater sludge was the factor controlling their elimination. In addition, that the vascular aquatic plants in the CW can be potential scavengers of metals accumulation. This study demonstrated that metal enrichment varies with metal type as well as the plant species.

5.5 Conclusions

CW system present several advantages. When the wetland system is constructed, there is no direct contact with the wastewater influent, no noise and odor generation, as compared with many other established treatment systems. CW systems can be implemented at any scale, enabling the onsite solution as a decentralized approach for wastewater treatment. CWs have also been proved efficient in reducing the pathogenic bacteria due to the HRT applied in these systems [3, 54], an issue of great importance for developing countries like Egypt. Generally, the pathogenic bacteria that are excreted in the sewage water live only for a short time depending on several factors including the surrounding environment and the bacteria own nature and characteristics [41]. It is found from the various experimental systems that pathogen removal in CWs is achieved via several mechanisms such as sedimentation, adsorption, filtration predation as well as inactivation due to the environmental stresses [23, 54].

Furthermore, CWs are a low-cost system in terms of construction, labor, maintenance and operation, since the labor needed to run the system are less than for other conventional technologies [1, 2, 39]. Typically, only one 1–2 hours weekly visit is required to control the site. Moreover, CW consume low amounts of energy or even no energy at all [29], since they use much less equipment than other systems. It is also worth mentioning that the CWs use no chemicals, therefore it is considered a green system.

A proper design of CW systems is crucial to obtain an acceptable effluent quality. The treated effluent has often a good quality suitable for land irrigation and safe reuse. This is mainly due to the removal of key pollutants such as ammonia, nitrates, phosphates, BOD5, COD, and TSS. Furthermore, the treated effluent can be safely reused for irrigation as the nutrient elements are recycled. In all cases, the treated effluent contains valuable nutrients (phosphates and nitrates) that give a high potential for agriculture irrigation. Moreover, reduction of sludge production can also be achieved through CWs [9, 62].

For these reasons, CWs have been efficiently used in Egypt for many years for treating various wastewaters, as a cost-effective, eco-friendly technology that could replace the conventional secondary biological treatment systems in many cases. The only drawback of these systems is the required land area for construction. However, usually this is not a problem in the arid and semi-arid areas where land is available and the water is highly needed. In Egypt, Middle Easter, North Africa, and generally in arid and semi-arid areas, and in many developing countries, the land area is often not a significant problem for the construction of a CW systems as a promising and attractive technique for decentralized wastewater management.

Acknowledgement This work is supported by the project titled "Towards Innovative and Green Water Reuse with Integrated Constructed Wetlands and Ferrate(VI) Treatment"- number (42688)-supported in whole or part by NAS and USAID, USA-Egypt Science Technology Joint Fund-(Cycle.19), (STDF), Egyptian Ministry of Higher Education and Scientific Research (MHESR).

This work is also supported by the project entitled "Development of the frame conditions for the establishment of an innovative water technology which couples anaerobic waste water treatment and biomass production in a bioreactor in the Mediterranean region" Project number (31319)-FRAME, ERANETMED3-75, (STDF), Egyptian Ministry of Higher Education and Scientific Research (MHESR).

References

1. Stefanakis AI (2020) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 503–525
2. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
3. Vymazal J (2010) Constructed wetlands for wastewater treatment: five decades of experience. Environ Sci Technol 45(1):61–69
4. Choudhary AK, Kumar S, Sharma C (2011) Constructed wetlands: an option for pulp and paper mill wastewater treatment. Electron J Environ Agric Food Chem 10:3023–3037
5. Stefanakis AI, Calheiros CSC, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sustainab 1:303–318. https://doi.org/10.1007/s43615-021-00022-3
6. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Piro P, Palermo SA, Turco M, Pirouz B, Stefanakis A, Regelsberger M, Ursino N, Carvalho PN (2021) Management of Urban Waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334
7. Mustafa A (2013) Constructed wetland for wastewater treatment and reuse: a case study of developing country. Int J Environ Sci Develop 4(1):20–24
8. Šereš M, Innemanová P, Hnátková T, Rozkošný M, Stefanakis AI, Semerád J, Cajthaml T (2021) Evaluation of hybrid constructed wetland performance and reuse of treated wastewater in agricultural irrigation. Water 13(9):1165. https://doi.org/10.3390/w13091165
9. Alwahaibi B, Jafary T, Al-Mamun A, Baawain MS, Aghbashio M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. https://doi.org/10.1016/j.jclepro.2021.126558
10. Mozaffari MH, Shafiepour E, Mirbagheri SA, Rakhshandehroo G, Wallace S, Stefanakis AI (2021) Hydraulic characterization and removal of metals and nutrients in an aerated horizontal subsurface flow "racetrack" wetland treating oil industry effluent. Water Res 200:117220
11. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
12. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, UK, pp 25–42
13. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233

14. Tromp K, Lima AT, Barendregt A, Verhoeven JTA (2012) Retention of heavy metals and poly-aromatic hydrocarbons from road water in a constructed wetland and the effect of de-icing. J Hazard Mater 203–204:290–298
15. Cai K, Elliott CT, Phillips DH, Scippo ML, Muller M, Connolly L (2012) Treatment of estrogens and androgens in dairy wastewater by a constructed wetland system. Water Res. 46:2333–2343
16. Breitholtz M, Näslund M, Stråe D, Borg H, Grabic R, Fick J (2012) An evaluation of free water surface wetlands as tertiary sewage water treatment of micropollutants. Ecotox Environ Safe 78:63–71
17. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10:127. https://doi.org/10.3390/app10010127
18. Dordio AV, Carvalho AJP (2013) Organic xenobiotics removal in constructed wetlands, with emphasis on the importance of the support matrix. J Hazard Mater 252–253:272–292
19. Kadlec RH, Wallace SD (2009) Treatment wetlands, 2nd edn. CRC Press, Boca Raton
20. Stottmeister U, Wiessner A, Kuschk P, Kappelmeyer U, Kastner M, Bederski O, Muller RA, Moormann H (2003) Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnol Adv 22:93–117
21. García J, Rousseau D, Morató J, Lesage E, Matamoros V, Bayona J (2010) Contaminant removal processes in subsurface-flow constructed wetlands: a review. Crit Rev Environ Sci Technol 40:561–661
22. Davies LC, Pedro IS, Ferreira RA, Freire FG, Novais JM, Martins-Dias S (2008) Constructed wetland treatment system in textile industry and sustainable development. Water Sci Technol 58:2017–2023
23. Abdel-Shafy HI, Dewedar A (2012) Constructed wetlands for urban wastewater treatment in Egypt. J Sustainab Sanitat Pract 12:27–32
24. Abdel-Shafy HI, El-Khateeb MA, Shehata M (2017) Blackwater treatment via combination of sedimentation tank and hybrid wetlands for unrestricted reuse in Egypt. J Desalin Water Treat 71:145–151
25. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2020) Treatment of cork boiling wastewater using a horizontal subsurface flow constructed wetland combined with ozonation. Chemosphere 260:127598
26. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
27. Tatoulis T, Stefanakis AI, Frontistis Z, Akratos CS, Tekerlekopoulou AG, Mantzavinos D, Vayenas DV (2017) Treatment of table olive washing water using trickling filters, constructed wetlands and electrooxidation. Environ Sci Pollut Res:1–8. https://doi.org/10.1007/s11356-016-7058-6
28. Mulidzi R (2010) Winery and distillery wastewater treatment by constructed wetland with shorter retention time. Water Sci Technol 61(10):2611–2615
29. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
30. Zhang DQ, Tan SK, Gersberg RM, Sadreddini S, Zhu J, Tuan NA (2011) Removal of pharmaceutical compounds in tropical constructed wetlands. Ecol Eng 37:460–464
31. Sandoval L, Zamora-Castro SA, Vidal-Álvarez M, Marín-Muñiz JL (2019) Role of wetland plants and use of ornamental flowering plants in constructed wetlands for wastewater treatment: a review. Appl Sci 9:685
32. Elbana TA, Bakr N, Karajeh F, El Quosy D (2014) Treated wastewater utilization for agricultural irrigation in Egypt. In: Proceedings of the national conference on water quality: challenges and solutions. National Research Centre, Cairo, Egypt. April 29th, pp 35–46
33. Saber M, Hoballah E, Abouziena H, Haggag WA, El-Ashry S, Zaghloul A (2016) Management of sewage farming in arid region: Egyptian experience. Int Sci Res J 72(3):116–123

34. Abdel-Shafy HI, Mansour MSM (2014) Biogas production as affected by heavy metals in the anaerobic digestion of sludge. Egypt J Pet 23(4):409–417. https://doi.org/10.1016/j.ejpe.2014.09.009
35. Abdel-Shafy HI, El-Khateeb MA (2019) Fate of heavy metals in selective vegetable plants irrigated with primary treated sewage water at slightly alkaline medium. Egypt J Chem. 62(12):2303–2312. Article 24
36. Abdel-Shafy HI, Kamel AH (2016) Groundwater in Egypt issue: resources, location, amount, contamination, protection, renewal, future overview. Egypt J Chem 59(3):321–362
37. Abdel-Shafy HI, Mansour MSM (2013) Overview on water reuse in Egypt: present and future. J. Sustainab Sanitat Pract 14:17–25
38. El-Hawary A (2015) Assessment of two natural wastewater treatment technologies to improve drainage water quality in the Nile Delta. Water Res Manag VIII 196:375–386
39. Abdel-Shafy HI, Mansour MSM (2020) Rehabilitation and upgrading wastewater treatment plant for safe irrigation reuse in remote area. Submitted for publication
40. Housing & Building National Research Center (HBNRC) (2004) The Egyptian manual as guidelines for treated waste water reuse in agriculture. Ministry of Housing & Utilities and New Communities, Cairo
41. El-Serehy HA, Bahgat MM, Al-Rasheid K, Al-Misned F, Mortuza G, Shadk H (2014) Cilioprotists as biological indicators for estimating the efficiency of using gravel bed hydroponics system in domestic wastewater treatment. Saudi J Biol Sci 21:250–255
42. Calheiros CSC, Stefanakis AI (2021) Green roofs towards circular and resilient cities. Circ Econ Sustain 1(1):395–411. https://doi.org/10.1007/s43615-021-00033-0
43. Iman OG (2014) The rise of rooftop gardens in informally developed areas in Egypt: exploring the abilities and boundaries. 6th international conference ARCHCAIRO 2014, Cairo, pp 208–223
44. Abdel-Shafy HI, El-Khateeb MA (2013) Integration of septic tank and constructed wetland for the treatment of wastewater in Egypt. J Desalinat Water Treat 51(16–18):3539–3546
45. Abdel-Shafy HI, El-Khateeb MA, Shehata M (2014) Greywater treatment using different designs of sand filters. J. Desalinat Water Treat 52(28–30):5237–5242
46. El-Khateeb MA, Saad MA, Abdel-Shafy HI, Samhan FA, Shaaban MF (2018) The feasibility of using non-woven fabric as packing material for wastewater treatment. Desalin Water Treat 111:94–100
47. El-Khateeb MA, El-Bahrawy A (2013) Extensive post treatment using constructed wetland. Life Sci J 10(2):560–568
48. Abdel-Shafy HI, El-Khateeb MA, Regelsberger M, El-Sheikh R, Shehata M (2019) Integrated system for the treatment of Blackwater and greywater via UASB and constructed wetland in Egypt. Desalin Water Treat 8:1–7. https://doi.org/10.5004/dwt.2009.788
49. Kamel M, El-Khateeb MA, Megahed R, Abdel-Shafy E (2010) Effect of entrance shape on the performance of constructed wetland. J Am Sci 6(9):787–795
50. Egyptian Environmental Affairs Authority "EEAA", 2009. Egyptian regulation: law 48, no. 61–63, permissible values for wastes in River Nile "1982" and law 9, law of the environmental protection
51. Abdel-Shafy HI, Regelsberger M, Masi F, Platzer C, El-Khateeb MA (2008) Constructed wetland in Egypt. Sustainable water management, journal of the EU project "sustainable concepts towards a zero outflow municipality". (Zer0-M), n 3/2008 3:10–14
52. Abou-Elela SI, Golinelli G, Saad El-Tabl A, Hellal MS (2014) Treatment of municipal wastewater using horizontal flow constructed wetlands in Egypt. Water Sci Technol 69(1):38–47
53. Alufasi R, Parawira W, Stefanakis AI, Lebea P, Chakauya E, Chingwaru W (2020) Internalisation of salmonella spp. by Typha latifolia and Cyperus papyrus in vitro and implications for pathogen removal in constructed wetlands. Environ Technol:1–35. https://doi.org/10.1080/09593330.2020.1811395
54. Stefanakis AI, Akratos CS (2016) Removal of pathogenic bacteria in constructed wetlands: mechanisms and efficiency. In: Ansari AA, Gill SS, Gill R, Lanza G, Newman L (eds) Phytoremediation, vol 4. Springer International Publishing, Switzerland, pp 327–346

55. El-Khateeb MA, Kamel M, Megahed R, Abdel-Shafy E (2016) Sewage water treatment using constructed wetland with different designs. Pollut Res 35(1):197–201
56. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360
57. Gaballah MS, Abdelwahab O, Barakat KM, Stefanakis AI (2022) A pilot system integrating a settling technique and a horizontal subsurface flow constructed wetland for the treatment of polluted lake water. Chemosphere 295:133844. S004565352200337X 133844. https://doi.org/10.1016/j.chemosphere.2022.133844
58. Abdel-Shafy HI, Al-Sulaiman AM (2014) Efficiency of degreasing/settling tank followed by constructed wetland for greywater treatment. Egypt J Chem 57(5):435–446
59. Abdel-Shafy HI, Cooper WJ, Handley-Raven LL, Casey LS (1986) Short-term fate of heavy metals in the gravel bed hydroponics wastewater treatment system. J Environ Protect Eng 12(1):61–80
60. Handley-Raven LL, Casey LS, Sutiha JL, Abdel-Shafy HI, Colley SB (1985) Gravel bed hydroponics for wastewater renovation and biomass production. Biomass and energy development, proceedings of the third southern research conference, 12–14 March, Gainesville, Florida, pp 287–302
61. Abdel-Shafy HI, Hegemann W, Teiner A (1994) Accumulation of metals by vascular plants-vascular plant can act as scavengers of metals from municipal wastewater while still maintaining a healthy status. J Environ Manag Health 5(2):21–24
62. Abdel-Shafy HI, Mansour MSM (2018) Phytoremediation for the elimination of metals, pesticides, PAHs, and other pollutants from wastewater and soil. In: Chandra R, Gurjan BR, Govil JN (eds) Environmental science and engineering, volume 6, toxicology. Studium Press LLC, Houston

Chapter 6
Constructed Wetland as an Efficient Technology for the Treatment of Urban/Industrial Wastewater in the Arid Regions: Morocco as a Model

Ayoub El Ghadraoui, Mounir El Achaby, Laila Mandi, Naaila Ouazzani, Fouad Zouhir, Abdeljalil El Ghadraoui, and Faissal Aziz

Abstract Human activities have caused holistic changes in earth climatic conditions, translated by decreased rainfall in many regions. Sadly, these changes are more expressed in poor and developing countries, especially in the African continent. Many regions suffer from long periods of drought and form water quality degradation, leading to waterborne diseases that spread dangerous diseases such as cholera and typhoid fever. To overcome these issues, many countries have adopted water management strategies based mainly on wastewater treatment and its reuse in agriculture to lower the pressure applied to freshwater resources. However, this could be a relevant issue in developing countries when using intensive systems such as activated sludge, membrane bioreactor, and sequencing batch reactors, due to their high costs in all steps of the wastewater treatment plant, from the construction

A. El Ghadraoui
Laboratory of Water, Biodiversity & Climate Change, Semlalia Faculty of Sciences, Cadi Ayyad University, Marrakech, Morocco

Department of Chemistry, University of Florence, Florence, Italy

M. El Achaby
Materials Science and Nanoengineering (MSN) Department, Mohammed 6 Polytechnic University (UM6P), Benguerir, Morocco

L. Mandi · N. Ouazzani · F. Aziz (✉)
Laboratory of Water, Biodiversity & Climate Change, Semlalia Faculty of Sciences, Cadi Ayyad University, Marrakech, Morocco

National Centre for Research and Study on Water and Energy (CNEREE), Cadi Ayyad University, Marrakech, Morocco
e-mail: f.aziz@uca.ma; faissalaziz@gmail.com

F. Zouhir
Unité Assainissement et Environnement, Université de Liège, Arlon, Belgium

A. El Ghadraoui
Department of Chemistry, University of Florence, Florence, Italy

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_6

(e.g., huge facilities, intensive technologies) to the exploitation (e.g., energy consumption, maintenance, qualified staff). On the other hand, extensive systems or low-cost technologies (e.g., infiltration-percolation, constructed wetland (CW), and algal pond) are more adapted to the developing countries' context due to their low cost in construction, easy operation and zero energy and chemicals' consumption. Among these systems, CW was distinguished from other systems not only by being a low cost and easy to implement technology but also by exhibiting great results in terms of wastewater treatment from both domestic and industrial activities (e.g., olive mill wastewater, tannery), achieving in some cases a high quality of water reusable in agriculture. Therefore, the CW technology has experienced a remarkable spread in developing countries, especially those under arid climates such as Morocco, one of the African leaders in water management. The aim of this chapter is to make a comparative analysis of wastewater treatment systems used in Morocco as an arid area and highlight the effectiveness of CW regarding its adaptation to the limited resources in this arid context and their treatment capacity for the different types of wastewater, including the tentative strategies for optimizing urban and industrial effluent treatment.

Keywords Constructed wetland · Urban wastewater · Industrial wastewater · Decentralized wastewater treatment plant · Morocco

6.1 Introduction

In arid and semi-arid areas where water is a limiting factor in crop production and the needs are often associated with population growth and increased levels of life, the volume of wastewater produced increases significantly. It will continue to increase steadily, especially the urban wastewater due to the cities broadening. Wastewater represents, in these conditions, an inexhaustible source. It is also the only water resource that will be more available in the future. Therefore, it is mandatory to take it into account and its wise management must be integrated into the sustainable development objectives, provided that they are refined. However, wastewater treatment (WWT) is almost absent in developing countries due to the high cost of investment and maintenance. It is, consequently, necessary to find reliable low cost techniques, capable of effectively treating wastewater.

For this purpose, CW (phyto-purification or filter planted with macrophytes) is an adequate alternative. CW is a water treatment system using aquatic plants, functioning as biological assimilators by eliminating both biodegradable and non-biodegradable compounds as well as nutrients, metals and pathogenic microorganisms [1]. Although of moderate cost, this system is not well established in the southern countries and its development has been observed mainly in rich countries because of its good treatment performance.

Morocco, characterized by an arid to semi-arid climate, is among the countries where water is scarce. The situation of its water resources is already critical and the risk of it becoming a problem hindering any further development is real. Average precipitation in Morocco is 27.18 mm annually from 1901 until 2015. Current per capita availability is 760,000 L/year, but that availability is expected to fall to 560,000 L/year by 2030 [2].

This critical situation of water resources has increased the interest in the reuse of treated wastewater in agriculture as an alternative solution and the integration of non-conventional water in a planning and mobilization strategy. Indeed, the water deficit can be filled mainly by treated wastewater; this resource is abundantly and continuously available. Moreover, it has many advantages, notably a reasonable cost compared to desalinating seawater or digging wells.

The direct benefits for the inhabitants of the cities and centers that this program will rehabilitate are estimated at 1.7 million euros per medium-sized center for access to an efficient service. Indirect benefits to the population's health and the Moroccan economy will be converted into improving the quality of surface water and groundwater, impacting economic activities, particularly tourism, agriculture, and the production of drinking water or water-using industries. A brief economic evaluation made it possible to calculate an Economic Internal Profitability Rate of 9%. In addition to these benefits, treatment and reuse of wastewater contribute to protecting the receiving environment [3]. For this reason, the Moroccan government launched a National Liquid Sanitation and Wastewater Treatment Program (PNA 2005–2030). The PNA is a very ambitious program that adopts a real action strategy to control and manage wastewater in Morocco. In addition, the PNA is targeting public access to the sanitation and WWT network.

This chapter reports the potential situation of alternative WWT in Morocco highlighting low-cost technologies, especially in the arid areas. A comparative approach to those treatment systems is envisaged. On the other hand, this work focuses on the experience of Morocco on the application of CW on industrial wastewater treatment.

6.2 The Current Status of Wastewater Treatment in Morocco

Morocco is a kingdom located in the northwest of Africa; it has 710,850 m^2, and 3500 km of coastline (500 km of Mediterranean and 3000 km of Atlantic Ocean). With insufficient rain and droughts and a population of approximately 34 million people, the mean volume of water available per inhabitant per year is about 1000 m^3/capita/year. However, in dry areas of Morocco, only 180 m^3 of water is available per inhabitant per year. The alarming evolution of drought and the complications linked to climate change have prompted the Moroccan government to set up the National Liquid Sanitation Plan (PNA) in 2005. The specific objectives for 2020 and 2030 were to achieve 80% overall connection to the urban sanitation network in 2020 and reach a volume of 60% of treated wastewater in 2020 [4].

Since the implementation of the PNA, several projects have been completed or are in the process of being completed. Therefore, the current situation is characterized as follows: increase in the rate of connection to the wastewater network to 75% (compared to 70% in 2005); Increase in the rate of WWT to 340.47 million m^3/year, i.e., 45% of the total volume against 8% in 2005, including 23% of the total volume treated at tertiary level; Construction of 140 WWTPs (compared to 21 in 2005) including 55 with tertiary treatment; 84 WWTP are in progress. The PNA aims to achieve a connection rate to the sanitation network in urban areas of 100% by 2030.

In Morocco, more than 750 million m^3 of wastewater is produced yearly. The ratio of treated wastewater to produced wastewater is equal to 24%. This ratio is considered among the lowest compared to other countries in the Mediterranean region, such as Egypt (57%) or Tunisia (79%) [4, 5].

Different technologies are used in Morocco to treat urban wastewater. Intensive systems (WWTP consuming high energy) such as activated sludge, membrane bioreactor, and sequencing batch reactor are implemented in major cities. Also, extensive systems (systems working with energy from natural resources es no energy) such as CW, stabilization pond and algal channel, are implemented in small villages (Fig. 6.1).

According to Aziz and Farissi [3], WWT processes require a consistent set of processes performed after pre-treatment, such as screening and degreasing. Both intensive processes, including activated sludge, biological drives and trickling filters, and extensive processes such as lagoons and infiltration-percolation beds. Since 1958, 60 WWTPs were built in Morocco. Yet, in 1994 the vast majority were down or not connected to the network for various reasons: inadequacy of the treatment system to meet local conditions, faulty design of structures, lack of maintenance, management problems (e.g., lack of budget, lack of competent technical staff), lack of planning in the short and long term. In 2004, only 8% of wastewater was treated; the rest was discharged directly into the sea (52%), the surface

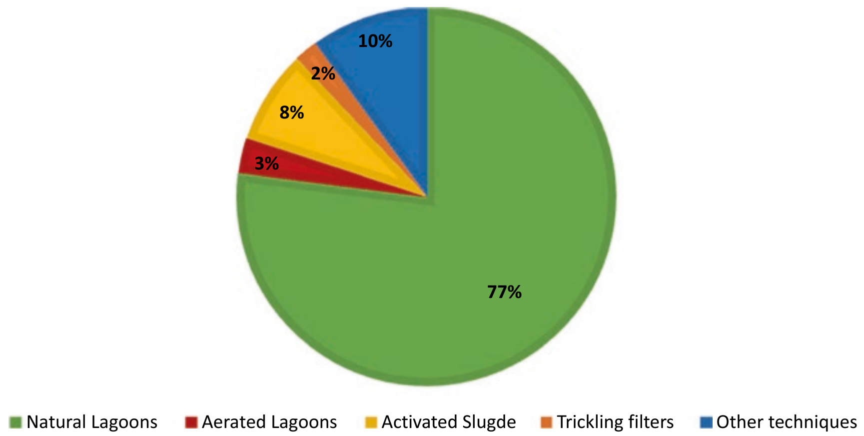


Fig. 6.1 Distribution of different kinds of WWT technologies in Morocco [3]

freshwater system (32%) and septic systems, causing serious pollution of the coastline, rivers and groundwater. This WWT rate was increased in 2012 to 28% [6]. By 2009, over 100 WWTPs are installed, mainly in small and medium-sized towns in the interior of the Moroccan country. They used various technologies such as activated sludge, ponds, drainage and stabilization ponds and infiltration filters. But the lagoon technology remains the most used in the country due to its low cost, simple maintenance and adaptation to climate conditions of the area [7]. For these 100 WWTPs, more than half are not functional for many reasons: technical, financial and human [7]. This situation demonstrates a delay that the country has experienced in successful wastewater technology deployment and contamination risks for the environment in general and water resources in particular. Therefore, to protect water resources and reduce pollution, a PNA has been developed to improve sewerage collection, treating both industrial and domestic wastewater and increasing wastewater reuse.

About 75–90% of treated wastewater in Morocco passes through secondary treatment to remove organic matter. Twenty-six WWTPs are equipped with tertiary WWT (disinfection step using chloride and UV irradiation), allowing the reuse of treated water. The largest WWTP in Morocco, which was built within the framework of the PNA, is that of Fez, which can treat 130,000 m^3/day and has a tertiary treatment process similar to that of the WWTP Marrakech (120,000 m^3/day). The latter, inaugurated at the end of 2011, makes it possible to meet the needs of 7 golf courses and the various green spaces. In addition, the WWTP manager (Autonomous Agency of Distribution of Water and Electricity of Marrakech, RADEEMA) has been able to conclude very specific commercial agreements with existing and future golf courses (for house garden's and the golf grass), i.e., 18 golf courses in total. To provide them with a perennial water supply of around 39 million m^3/year [8].

In terms of treated wastewater valorization, only 0.3% of wastewater is treated and reused in irrigation in Morocco [4]. The fraction of the irrigation area equipped for irrigation with treated wastewater varies between 1% and 2%. While, the fraction equipped for irrigation by direct use of untreated wastewater is 0.5%. The constraints leading to these poor levels of wastewater reuse is lack of social acceptance due to inadequate information on the benefits of this practice and to the poor monitoring of treated wastewater, incomplete economic analysis of WW reuse options, a mismatch between water pricing and water scarcity, and lack of economic incentives for treated wastewater reuse [9–11].

In Morocco, WWTP suffers from different issues such as substantial delays and high costs for the purchase of components for repairing equipment; insufficient aeration in the secondary treatment, due to power outages or high cost of energy; WWTPs operating above their capacity due to rapid population growth; failures of the secondary process due to the presence of toxic compounds carried by untreated industrial wastewater and insufficient monitoring of treated wastewater quality due to legal or technical constraints.

6.3 Comparative Approach for Wastewater Treatment

According to the World Bank, 21% of transmissive diseases (e.g., Bilharzia, Trachoma, Hookworm, Diarrhea, Ascariasis) are water-related due to the presence of microbial populations such as protozoan fungi, viruses, bacteria, helminths and algae [12] (Fig. 6.2). About 6939 annual deaths were documented for 13 diseases caused by pathogens transmitted by water. In addition, 91% were associated with three environmental pathogens that can grow in water system biofilms: Legionella (Legionnaires' disease) (250 deaths), Nontuberculous mycobacteria (NTM, 1216 deaths), and Pseudomonas-related pneumonia (1618 deaths) or septicemia (3217 deaths). Furthermore, 7% were associated with seven pathogens transmitted by the fecal-oral route: Campylobacter, Cryptosporidium, *E. coli*, Giardia, Hepatitis A, Salmonella non-typhoidal and Shigella [13, 14].

Wastewater could also be harmful to humans and the environment by the presence of some major chemical pollutants such as heavy metals, pesticides, nitrogen, phosphors and detergents [12]. In order to eliminate or reduce the concentration of these pollutants in wastewater, WWTP has been used since ancient times [15, 16]. Generally, from about 1900 to the early 1970s, treatment was used in order to remove suspended and floatable material from wastewater, organic matter and pathogenic microorganisms. However, from the early 1970s to about the 1990s, WWT focused more on aesthetic and environmental concerns by removing suspended solids, organic matter and pathogenic microorganisms and targeting more pollutants such as nitrogen and phosphorus been the cause for lake eutrophication. Since 1990, increased scientific knowledge has targeted more toxic pollutants in the treatment process, such as heavy metals, pesticides and pharmaceuticals [17].

WWTP could be classified as centralized or decentralized systems. Centralized systems, also known as conventional treatment, are usually publicly owned and used to treat wastewater collected from cities of larges communities via a complex

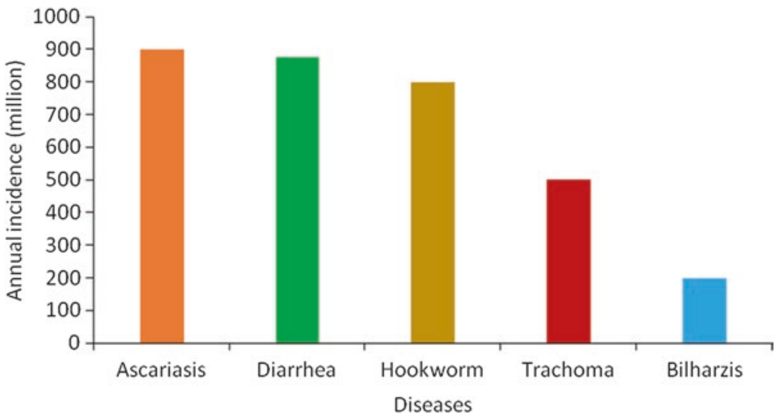


Fig. 6.2 Diseases due to lack of sanitation services around the world

sanitation network, major excavations and manholes for access. Thus, centralized systems require less public contribution and responsiveness [18]. However, in order to collect and treat wastewater, centralized systems require materials (pumps and piping materials) and energy, consequently increasing the implementation and operation costs [19–21].

A centralized wastewater treatment system is more complex, combining screening, primary treatment, secondary treatment, tertiary treatment (disinfection). It treats wastewater in a central location and then redistributes or discharges treated wastewater via dedicated distribution networks. The system commonly used in this centralized approach is activated sludge (Fig. 6.3).

A centralized wastewater treatment system can treat large volumes of water at high rates to accommodate all residential, business, and industrial uses. However, the capital cost and operating and maintenance costs for a centralized system can be significant. It consists of water source development, construction of significant infrastructures (e.g., the treatment facility, reservoir, and water distribution main), implementation of automated monitor and control systems, and onsite operators. Furthermore, the cost is considerable during the operation as multiple fees are needed (e.g., water discharge fee, electric fee, chemical fee, sludge transport and disposal fee, staff cost, administration cost) [19–21].

On the other hand, decentralized systems are often implemented for the treatment of individual homes or buildings. They are designed to operate on a small scale and are generally implemented in rural or peri rural communities in low-income countries (Table 6.1). Decentralized systems play a role in environmental preservation and also in decreasing freshwater use by reusing treated wastewater. Moreover, decentralized systems can be implemented on an as-needed basis, evading the costly implementation of centralized treatment systems.

The most commonly used decentralized treatment techniques are i) primary treatment ii) secondary treatment. Primary treatment is generally used for the removal of settleable solids in order to prevent damages of material in the following treatment step; the removal of settleable solids will also participate in the decreasing of sludge production. Septic tank is the most common system used as primary treatment. Besides removing settleable solid's function, the septic tank can also be used as an anaerobic bioreactor to enhance organic matter removal. Furthermore, by injecting air bubbles, the septic tank can also remove oils and hydrocarbons by

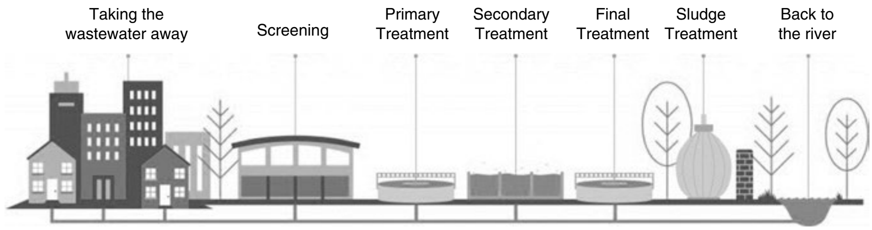


Fig. 6.3 Typical layout of centralized wastewater treatment systems

Table 6.1 Summary of hypothetical EPA rural community technology costs (1995 US$) [22]

Technology	Total capital cost (US$)	Annual operation and maintenance cost (US$)	Total annual cost (US$)
Centralized system	2,321,840–3,750,530	29,740–40,260	216,850–342,500
Alternative small-diameter gravity sewers	598,100	7290	55,500
Collection and small cluster systems	510,000	13,400	54,500

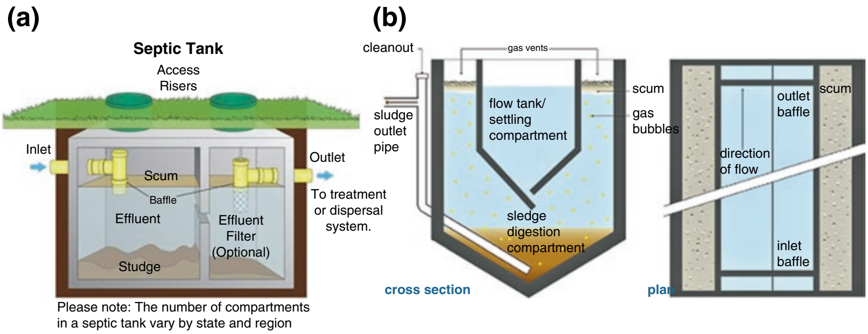


Fig. 6.4 Schematic representation of (**a**) septic tank and (**b**) Imhoff tank (available at https://www.epa.gov/septic/types-septic-systems)

flotation. Imhoff tank is also used as primary treatment; its design allows a higher flow rate than the septic tank; nevertheless, it is less common. (Fig. 6.4).

Many secondary treatment systems such as (i) filters (e.g., sand filter) (ii) lagoon (e.g., facultative lagoons, aerated lagoons, anaerobic lagoons, aerobic lagoons) (iii) aerobic systems (e.g., suspended growth, sequencing batch reactor, attached growth, CW) are used as decentralized WWTP (Table 6.2).

Other treatments or disposal technics used in decentralized WWT are evaporation, surface discharge and reuse. Subsurface wastewater infiltration, land application and CWs could also be counted as treatment and disposable methods. The particularity of treatment and disposal technics is to provide a further polishing treatment before final disposal of reuse [30]. Decentralized systems can be engineered for a specific location, thus overcoming the problems associated with site conditions such as impervious soils, high groundwater tables, limestone formations and shallow bedrock. Moreover, decentralized systems allow for flexibility, considerable modification in the process to meet treatment goals and address environmental and public health protection requirements. The objectives of wastewater management in relation to the characteristics of decentralized treatment systems are represented in Fig. 6.5.

A decentralized treatment system can demonstrate some problems, such as the overflowing of wastewater into the surrounding areas in case of improper management of a septic tank, which can cause detrimental health impacts [31, 32]. Currently,

Table 6.2 Removal rates (%) of various decentralized WWT technologies

	Type	COD	TSS	N	P	FC	Reference
Media filters	Intermittent sand filter	94	94	87	97	–	[23]
	Recirculating sand filter	99.3	100	44.4–90.9	43	–	[24] [25]
Lagoons	Aerobic lagoons	25.0–65.2	–	–	–	–	[26]
	Aerated lagoons	68	63	50	54	–	[27]
	Anaerobic lagoons	70–80	–	–	–	–	[28]
CWs		96.1	97	99.6	91	68.3	[29]

COD chemical oxygen demand, *TSS* total suspended solids, *P* phosphorus, *N* nitrogen, *FC* fecal coliform

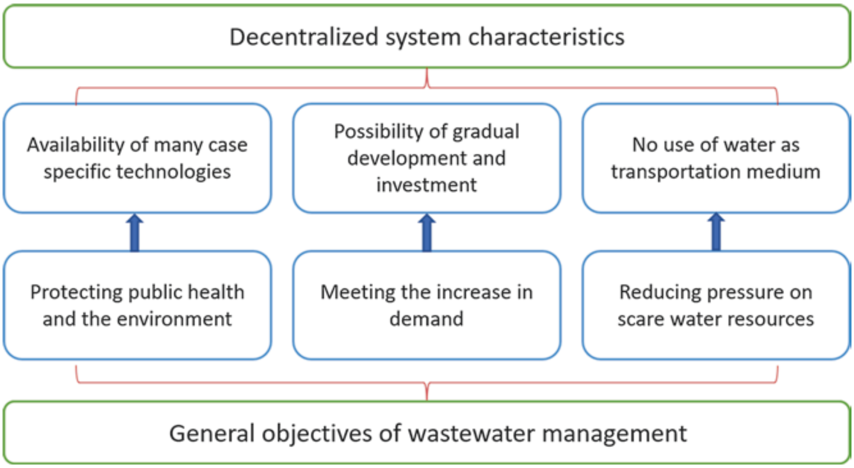


Fig. 6.5 General objectives of wastewater management versus decentralized systems characteristics

sustainability has become a core issue of wastewater management. Yet, the systems offered for sustainable management (centralized) are expensive enough that a developing country cannot adopt them [33]. Therefore, numerous secondary treatment systems exist for decentralized wastewater treatment, each having advantages and disadvantages (Table 6.3). Considering that sand is the most common and available substrate for filters, the media filter is occasionally equal to the sand filter. Commonly, in areas with deep, permeable soils, septic tank–soil absorption systems can be used. On the other hand, more complicated onsite systems will be required in zones with shallow, very slowly permeable or highly permeable soils.

In Morocco, especially in arid areas, as the Tensift El Haouz region, the climate reigning over the entire basin is arid to semi-arid with oceanic influence near the coasts. Due to its size and relief, the region is characterized by a very different climate from an area to another. The climate is semi-arid, influenced by the cold Canary current in the coastal zone, hot semi-arid Jbilet, arid continental current in Haouz and Mejjat.

Table 6.3 Advantages and disadvantages of the most common secondary treatment methods [14, 31, 34–37]

Unit	Main advantages	Main disadvantages
Media filters: Intermittent sand filter (ISF) and recirculating sand filter (RSF)		
Filters	Minimum and easy operation and maintenance High quality effluent especially for BOD and TSS. Nitrogen can be completely transformed to nitrate if aerobic conditions are present No chemicals required	Cost may increase if the media is not available locally Regular maintenance required Clogging is possible Electric power is needed The land area required may be a limiting factor
Lagoons		
Facultative lagoons (FL) and aerated lagoons (AL)	Effective in the removal of settleable solids, BOD, pathogens, and ammonia Effective at removing disease-causing organisms High-nutrient and low pathogen content effluent Cost-effective in areas where land is inexpensive Require less energy than most other WWT systems Can handle periods of heavy and light usage The effluent can be used for irrigation because of its high nutrient and low pathogen content Easy to operate and maintain	Not very effective in removing heavy metals Do not meet effluent criteria consistently throughout the year Often require additional treatment or disinfection to meet state and local discharge standards Sludge accumulation is higher in cold climates Mosquitoes and insects can be a problem if vegetation is not controlled Odor may be a problem Require more land area than other WWT systems Less efficient in cold areas and thus may require a longer retention time
Anaerobic lagoons (AnL)	Effective at removing disease-causing organisms More effective for strong organic waste Produce methane and less biomass per unit of organic loading Cost-effective (not aerated or heated) Effluent can be used for irrigation because of the high nutrient content Generally low sludge production Simple to operate and maintain	Not very effective in removing heavy metals Often require additional treatment or disinfection to meet discharge standards Require a relatively large area of land Odor production Not suitable for domestic wastewater with low BOD. Levels
Aerobic lagoons (AoL)	Effective at removing disease-causing organisms (5e) Simple to operate and maintain Effluent can be used for irrigation because of the high nutrient and low pathogen content	Not very effective in removing heavy metals from the wastewater Often require additional treatment or disinfection to meet discharge standards Require large land areas

(continued)

Table 6.3 (continued)

Unit	Main advantages	Main disadvantages
Aerobic treatment		
Suspended growth (SG)	Extended aeration plants produce a high degree of nitrification since hydraulic and solid retention times are high Extended aeration package plants are available on the market	Some odor and noise may be issued Require electricity Require regular operation and maintenance
Sequencing batch reactor (SBR)	Suitable for site conditions for which enhanced treatment, including nitrogen removal, is necessary for protecting local ground and/or surface water The lower organic and suspended solids content of the effluent may allow a reduction of land area requirements for subsurface disposal systems	Relatively high initial capital costs Operational control and routine periodic maintenance is necessary to ensure the proper functioning of this type of treatment system Maybe most applicable to cluster systems
Attached growth (AG)	Better capturing of suspended solids than the suspended growth Less complex than extended aeration systems Very minimal operation is needed	Nitrification can occur at low loading rates in warm climates Very few commercially produced fixed films systems are currently available for onsite application Require electricity
Constructed wetlands (CWs)	The lower organic and suspended solids content of the effluent may allow a reduction of land area requirements for subsurface disposal systems Inexpensive to operate and construct Reduced odors Able to handle variable wastewater loadings Reduces land area needed for wastewater treatment Provide wildlife habitat	Some maintenance of wetland units will be required periodically The area of a site occupied by the wetland would have very limited use Require a continuous supply of water Affected by seasonal variations in weather conditions Can be destroyed by overloads of ammonia and solids levels Remove nutrients for use of crops

According to the 2014 Regional Planning Directorate of the Marrakech-Safi Region (RGPH) statistics, the population of the Tensift basin is 3,307,586 inhabitants, compared to the populations established according to the previous RGPH (1994 and 2004), respectively 2,575,742 inhabitants and 2,909,029 inhabitants. Thus, the rates of the population increase in the Tensift basin stand at 1.2% for 1994–2004 and 1.3% for 2004–2014.

For a quantity of 140,000 m^3/day of wastewater discharged by the region, the prefecture of Marrakech discharges the largest volume; this represents 66% of the total volume. The other provinces had relatively insignificant releases; they presented between 1% and 10% of the total volume of the region. Therefore, the

Table 6.4 Treatment performance of all ecological WWTP in the Tensift Al Haouz arid region (Data not published)

Site	System	Removal rate (%)		
		TSS	COD	BOD_5
Aghouatim	Multi soil layers	80.92	55.72	67.07
Tidili Mesfioua	Infiltration percolation	89.53	84.66	87.24
	CW	97.30	88.59	87.41
Asni		93.66	88.56	96.40
Tamsloht	Natural lagoon	77.37	76.16	83.62
Saada		52.13	66.87	48.64
Chichaoua		63.69	64.58	63.92
Sidi Mokhtar		38.56	58.10	66.73
Essaouira		42.06	56.49	70.28

prefecture of Marrakech is the one that exerts the most pressure in terms of wastewater discharges; it should, however, it should be noted that it is the most urbanized prefecture, and therefore the best connected to sanitation and drinkable water network.

Table 6.4 shows the performance of the WWT by the different ecological processes in the region. High yields were recorded for BOD_5 and COD at planted filters, compared to all region systems, with removal yields of 93 and 96% of BOD_5, respectively, for Tidili and Asni, and a yield of 89% for COD for both systems. The physical and microbial mechanisms played an important role in removing BOD_5 and COD by planted filters. Due to the physical filtration mechanisms and the low porosity of the gravel medium, organic solids can be percolated and captured in the marsh bed for a long time, resulting in greater biodegradation. Sedimentation of suspended solids and rapid decomposition processes also result in high removal rates for COD and BOD_5 [38]. The results of the present study are in agreement with the literature regarding the rate of reduction of organic matter [39]. Thanks to the efficiency of CWs in this region, the quality of the treated wastewater allow their reuse in agriculture according to the Moroccan irrigation standards.

6.4 Constructed Wetlands for Domestic Wastewater Treatment under Different Operation Conditions in Morocco

Several full-scale CWs are implemented in Morocco, especially in rural areas and small communities, and are dedicated to domestic wastewater treatment. Unfortunately, very few case studies are published in the form of scientific papers and reports. In Morocco, a hybrid CW (horizontal + vertical) implemented in the arid region of Marrakech was monitored and the results show high removal efficiencies [7]. The implementation consisted of three parallel lines planted with different

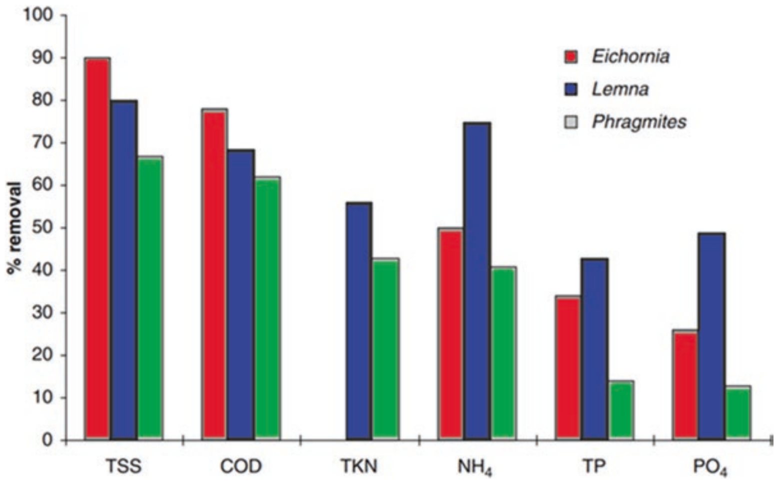


Fig. 6.6 Removal efficiency of CWs with different plant species

species (*Eichornia, Lemna, Phragmites).* The results of the monitoring are demonstrated in Fig. 6.6.

In the suburban area of Casablanca (Douar Ouled Ahmed), a full-scale CW was implemented for the treatment of Hammam (Municipal bath) effluent and its reuse for agricultural irrigation [40] (Fig. 6.7).

The implemented CW (Vertical flow) was planted with *Phragmites australis* and was designed to treat 6–10 m^3/day to irrigate a surface area of 1000 m^2. In terms of treatment, no specific data was reported regarding the inlet and outlet of several pollutants. However, the author has reported that the implemented system has shown significant removal efficiency towards removing organic matter in forms of COD and BOD since the final effluent complies with the Moroccan regulation for the reuse of treated wastewater in irrigation [41].

El Hamouri et al. [42] have monitored the removal efficiency of a full-scale CW in the city of Rabat (latitude 30°03′ N, longitude 6°46′ W) 73 m above the Atlantic Ocean level. Average temperatures are 14 °C and 27 °C, respectively, in the cold and the hot season. The treatment plant consisted of the combination of TSUAR (two-step up anaerobic flow reactor) pre-treatment system, high-rate algae pond and subsurface-horizontal flow CW (SSF-h) system. Three parallel SSF-h beds receiving around 9.5 m^3/day; two were planted with *Arundo* and *Phragmites* and the third remained unplanted. The removal efficiencies (Table 6.5) were significantly high in the planted systems; the system planted with *Arundo* demonstrated a removal of 82%, 82%, 79%, 79%, 11%, 8%, 15%, 33% and *Phragmites* 78%, 79%, 80%, 78%, 8%, 9%, 15%, 17%, respectively, for COD, BOD_5, TSS, VSS, TKN, NH_4^+, TP and PO_4^{3-}. In the unplanted system, the removal efficiencies were lower as it has showed removals of 66%, 68%, 60%, 56%, 8%, 5%, 15%, 17%, respectively, for COD, BOD_5, TSS, VSS, TKN, NH_4^+, TP and PO_4^{3-}.

Fig. 6.7 Pictures of the implemented constructed wetland in Casablanca

Table 6.5 Removal efficiency of the full-scale CW in Rabat for beds with different plant species and the unplanted bed

	Removal efficiency (%)		
Parameters	Arundo	Phragmites	Unplanted
COD	82	78	66
BOD_5	82	79	68
TSS	79	80	60
VSS	79	78	56
TKN	11	8	8
NH_4^+	8	9	5
TP	15	15	15
PO_4^{3-}	33	17	17

In another study conducted in the region of Marrakech, Elfanssi [39] has evaluated the efficiency of a hybrid CW. The full scale is implemented in the rural mountainous area of Tidili (Fig. 6.8).

The treatment system was designed to treat domestic effluent. It consisted of three vertical flow CWs working in parallel, followed by two horizontal-subsurface flow CWs with a hydraulic load of 0.5 $m^3/m^2/d$ and 0.7 $m^3/m^2/d$, respectively (Fig. 6.9).

In terms of performance, the treatment plant studied by Elfanssi [39] has demonstrated significant removal efficiencies of several pollutants. As reported, the system managed to remove 95%, 93%, 91%, 67% and 62%, respectively, for TSS, BOD5,

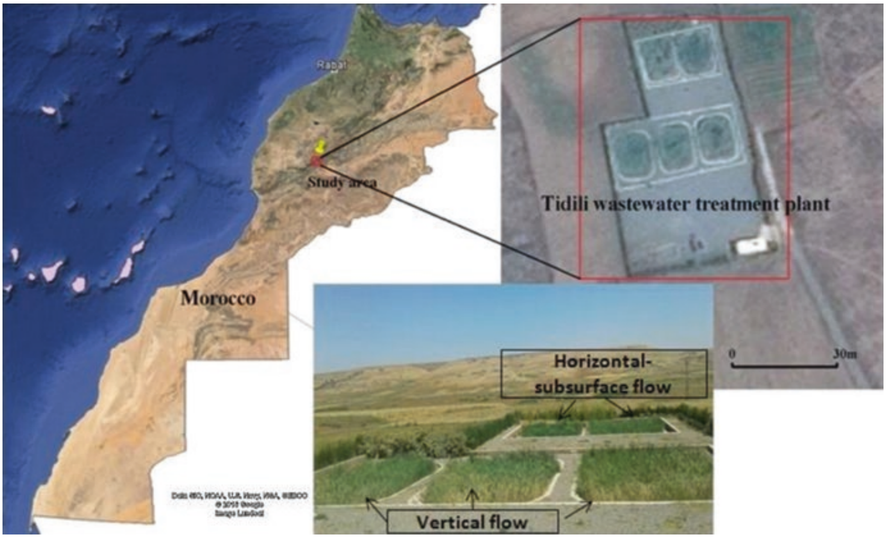


Fig. 6.8 Images of the implemented CW in a rural area of Marrakech

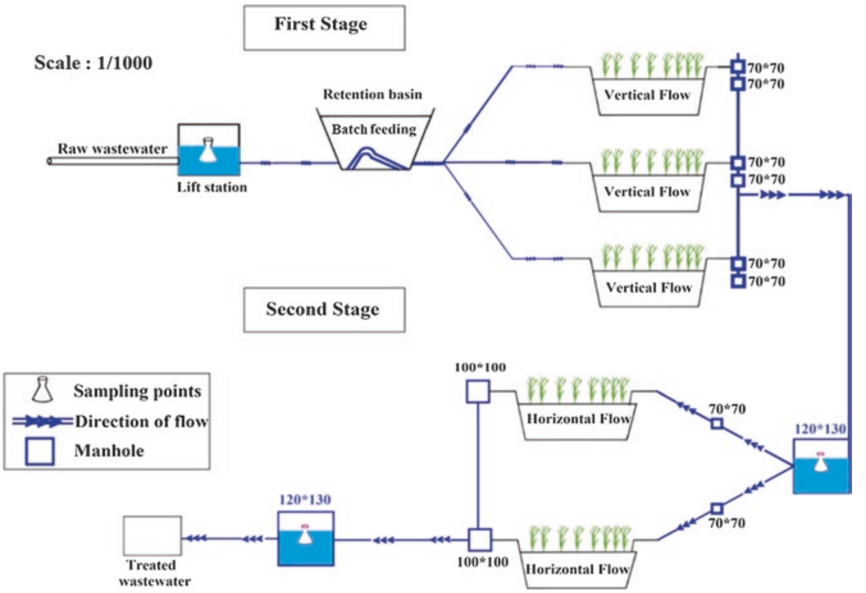


Fig. 6.9 Schematic representation of the hybrid CW for the treatment of domestic wastewater in a rural area of Marrakech

COD, TN and TP. In addition, the system demonstrated high performance in terms of total coliforms, fecal coliforms and fecal streptococci removal (4.46, 4.31 and 4.10 Log units, respectively).

6.5 A Pilot CW for Urban and Industrial Wastewater Treatment in an Arid Area of Morocco

In Morocco, CW is mostly used for the treatment of domestic wastewater in small villages and small communities. However, the economic state and the amount of produced wastewater do not allow the implementation of an intensive WWTP. In the region of Meknes, Taouraout et al. [43] studied the performance and the sustainability of a pilot vertical flow CW designed to treat domestic wastewater. The pilot CW was implemented in a school and had the following dimensions of L:W:H = 0.4 × 0.6 × 0.78 m. The CW was planted with *Chrosopogon zizanioides L.* at a density of 4 plants/m^2 (Fig. 6.10).

The pilot was filled from the top with fine gravel (infiltration layer), medium gravel (transition layer), iron sawdust (iron layer) and drainage layer (crushed concrete). This system was fed with three hydraulic loading rates: 250 L/m^2/day, 350 L/m^2/day and 500 L/m^2/day. As for the performances, the removal efficiencies were 74–92%, 68%, and 47%, respectively, for COD, orthophosphates and ammonium. The final effluent complied with the Moroccan regulation for the reuse of treated wastewater in irrigation and, therefore, could be used for the irrigation of certain crops varieties.

In the case of industrial wastewater, CW are not used. However, few published studies present the CW as a promising technology that can achieve a high removal rate while resisting a high toxic effluent. For example, in Morocco, a recent study on the feasibility of CW for the treatment of olive mill wastewater was conducted [44]. In the study, a pilot vertical flow CW was used planted by *Phragmites australis* (Fig. 6.11). The pilot CW received highly toxic olive mill wastewater from a traditional extraction unit; olive mill wastewater had a high concentration of organic matter expressed (264 g COD/L), high conductivity (28 mS/cm), high suspended solids (2066 mg/L) and high phenolic content (8.73 g/L) (Table 6.6). Due to the high toxicity of the effluent, the latter was diluted using urban wastewater to increase

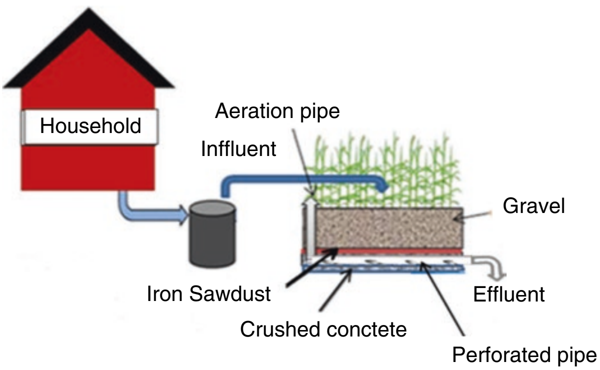


Fig. 6.10 Schematic representation of the pilot CW for the treatment of wastewater from a school in Meknes

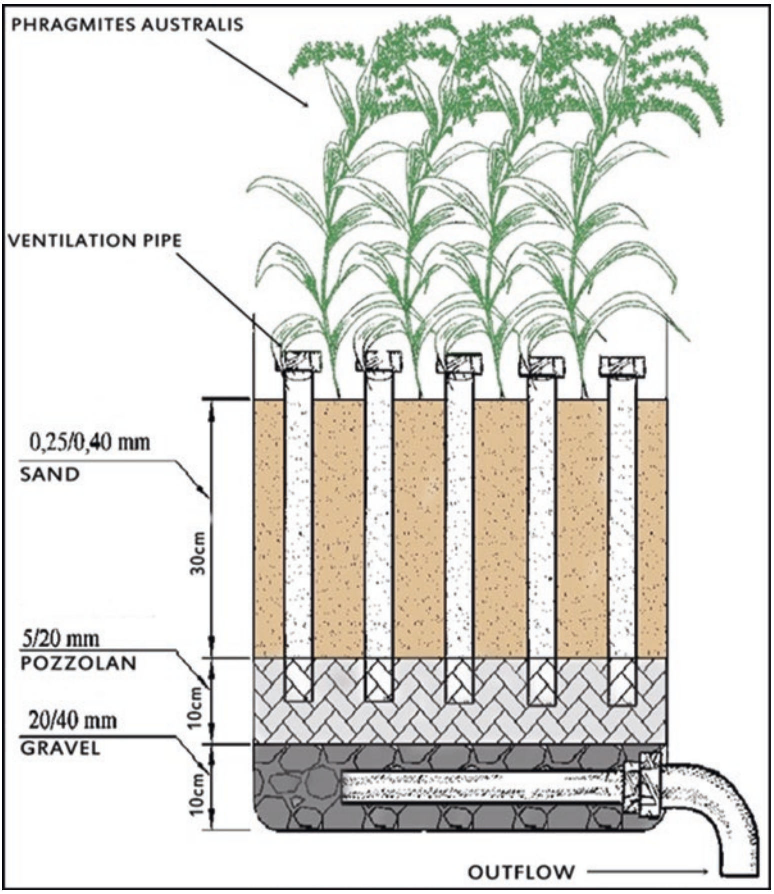


Fig. 6.11 Schematic representation of the pilot CW for olive mill wastewater treatment

the ratio of microorganisms that participate in the biodegradation processes inside the CW.

The dilution using urban wastewater also allows the treatment of two effluents at the same time. Results obtained after one year monitoring showed that the CW had high removal rates regarding the major pollutants present in olive mill wastewater, i.e., 91%, 89%, 95%, 94%, 58%, 92% and 96%, respectively, for COD, polyphenols, PO_4^{3-}, P, SO_4^{2-}, NO_2^- and NH_4^+ [45, 46]. The phytotoxicity and antimicrobial effect of olive mill wastewater are due to their polyphenol content. The removal of specific toxic polyphenol compounds was also investigated (e.g., hydroxytyrosol, tyrosol) using the liquid chromatography technique. The study showed that the CW completely removed these phenolic compounds. The same system was also used to study the removal of polychlorobiphenyl (PCB) [46], showing that certain classes of PCB were removed at a removal rate between 14% and 100%. The treated wastewater produced in this study complied with the Moroccan regulation for treated

Table 6.6 Characterization of the olive mill wastewater treated in a CW

Parameters	Unit	Olive mill wastewater
pH	–	5.01
Dissolved oxygen	Mg/L	0.70
Electrical conductivity (EC)	mS/cm	28.23
Total dissolved salts	g/L	22.10
Total suspended solids	Mg/L	2066 ± 11.27
Total polyphenol	g/L	8.73 ± 0.43
Chemical oxygen demand (COD)	g/L	264 ± 11.49
Orthophosphate $PO_4^{3}-$	Mg/L	31.14 ± 0.65
Sulfate $SO4^{2}-$	Mg/L	1320 ± 0.05
Ammonium NH_4+	Mg/L	6.33 ± 0.30
Nitrate NO_3-	Mg/L	1.32 ± 0.05
Nitrite NO_2-	Mg/L	96.23 ± 9.41
Phosphorus P	Mg/L	41.61 ± 4.37
Total coliform	UFC/100 ml	0
Fecal coliform	UFC/100 ml	0
Fecal streptococcus	UFC/100 ml	0

wastewater reuse in agriculture. It was used to irrigate olive trees in another study [47]. Collected data have shown that olive trees demonstrated an increase in biomass, leaves number, height, and diameter of the plant [47].

In another work regarding the treatment of industrial wastewater in a CW, the removal of chromium from tannery wastewater in Marrakech was studied [48]. The objective of this study was to test the performance of the rooted aquatic plant *Phragmites australis* in purifying the tanning effluent with high chromium concentrations in a vertical flow CW. The interest is particularly focused on comparing a pilot planted by *Phragmites Australis* with an unplanted pilot. The pilot consists of pots with a capacity of 120 L, filled to a thickness of 15 cm with gravel and 60 cm of soil. Three pots are planted with young stems of *Phragmites australis (Cav.) Steudel* (36 stems/m^2). Three other unplanted pots were taken as control. The two pilots were irrigated with tanning water at increasing levels of total Chromium: 10% (March), 20% (April), 30% (May), 40% (June), 50% July). Dilutions were made with well water to allow *Phragmites australis* to adapt and grow at the start of the experiment. The systems were fed with 10 L/day for three successive days followed by a 4-day rest period. This chosen feeding mode helps maintain aerobic conditions and prevent clogging.

Physiological symptoms at the plants were observed at the 40% (Cr = 720 ± 35 mg/L) and 50% (Cr = 780 ± 196 mg/L) dilution: i) drying out of the ends of some leaves, ii) new young shoots of *Phragmites australis* have appeared. To test the plant, the experiment was carried out with 50% dilution (Cr = 780 ± 196 mg/L), which corresponds to the full chromium content that *Phragmites australis* can withstand.

Table 6.7 Characterization of tannery wastewater fed to a pilot CW

Parameters	Unit	Concentration
pH		3.08
Electrical conductivity	mS/cm	118
Total suspended solids	Mg/L	233
Biological oxygen demand		45
Chemical oxygen demand		2500
Ammonium		
Chromium		5
Chloride	g/L	20.6

Table 6.7 shows that the tannery used in this study is characterized by high COD (2500 mg/L), high ammonium (520 mg/L), high electrical conductivity (118 mS/Cm), chromium concentration (1230 mg/L) and considerable concentration of chlorine (20.6 g/L). Obtained results have shown a negative removal effect for some parameters, such as the electrical conductivity that increased from 54 mS/cm to 75 and 68 mS/cm. CW has shown a removal efficiency of 60% in terms of COD. Total chromium mean removal was at 99%.

Despite the shorter residence time in the Phragmites bed, a reduction in total chromium (= 99%) comparable to that of the unplanted soil bed (where the residence time is three times greater) was found. The results of this study confirmed the overall performance of macrophyte systems in treating chromium tanning effluent in an arid climate and under the experimental conditions adopted [49]. The intermittent supply adopted to the two systems ensures better aeration of the soil. Consequently, using a substrate of a coarse nature (88% sand) in the presence of the helophytes reduces the risk of clogging. *Phragmites australis* could be used to reduce heavy metals, particularly chromium, to treat industrial wastewater [48]. Collected data showed that the treatment of tannery wastewater by CW is a green, ecological approach that could constitute a viable alternative compared to mechanical/advanced technologies for tannery WWT [48].

6.6 Conclusion

This chapter reports the status of wastewater treatment in Morocco as an alternative approach towards water scarcity, highlighting low-cost technologies, especially in arid areas. A comparative approach to those treatment systems has been envisaged, which shows that wastewater treatment by the different ecological processes presents high yields for BOD_5 (96%) and COD (89%) in planted beds compared to all systems. Furthermore, this work highlights the treatment efficiency of a hybrid CW (horizontal + vertical) implemented at full-scale for a rural population in an arid region. This showed the best removal capacity of the hybrid CW than typical single stage systems under different operation conditions. Other successful experiences of CW application for urban wastewater treatment are also presented around the biggest cities in Morocco (Casablanca and Rabat) with 82% removing of COD and BOD_5. Moreover, this chapter showed experiences in Morocco using CWs for industrial/urban wastewater treatment. The first experience demonstrated the CWs capacity in the treatment of olive mill wastewater (mixed with domestic wastewater) in removing toxic elements (89% of polyphenols). Another full-scale system treated tannery effluent with high chromium concentrations under a vertical flow regime, showing good chromium removal performance (99%). Those successful examples in Morocco present the CW as a promising and appropriate technology that can achieve high removal rates while resisting a high toxic effluent.

References

1. Kantawanichkul S, Duangjaisak W (2011) Domestic wastewater treatment by a constructed wetland system planted with rice. Water Sci Technol 64:2376–238064. https://doi.org/10.2166/wst.2011.806
2. Kurtze JB, Thompson HJ, Platko EJ, Morais MJ (2015) Advancing water management strategies in Morocco. Association Ribat Al Fath Pour le Developpement Durable 53pp. Accessible at: https://web.wpi.edu/Pubs/E-project/Available/E-project-101615-040211/unrestricted/IQP-Sponsor_Edition.pd
3. Aziz F, Farissi M (2014) Reuse of treated wastewater in agriculture: solving water deficit problems in arid areas. Ann West Univ Timis Ser Biol 17(2):95–110
4. FAO (2017) AQUASTAT website. Rome (IT). [cited 2017 July 10]. http://www.fao.org/nr/water/aquastat/main/index
5. Nikiema J, Figoli A, Weissenbacher N, Langergraber G, Marrot B, Moulin P (2013) Wastewater treatment practices in Africa-experiences from seven countries. Sust Sanit Pract 14:26–34
6. Rifki M (2013) Programme National d'Assainissement Liquide et d'Epuration des Eaux Usées. Ministere de L'interieur, Direction Générale des Collectivités Locales, Direction de L'eau et de L'assainissement
7. Mandi L, Bouhoum K, Ouazzani N (1998) Application of constructed wetlands for domestic wastewater treatment in an arid climate water. Sci Technol 38(1):379–387
8. RADEEMA (Régie Autonome de Distribution d'Eau et d'Electricité de Marrakech) (2009) Rapport de Traitement et Réutilisation des Eaux Usées de la Ville de Marrakech
9. Jeuland M (2015) Challenges to wastewater reuse in the Middle East and North Africa. Middle East Dev J 7:1–25
10. Choukr-Allah R (2011) Innovative wastewater treatment and reuse technologies adapted to southern Mediterranean countries. In: Barceló D, Petrovic M (eds) Waste water treatment and reuse in the Mediterranean region. Springer, Dordrecht, pp 29–41
11. Qadir M, Bahri A, Sato T, Al-Karadsheh E (2010) Wastewater production, treatment, and irrigation in Middle East and North Africa. Irrig Drainage Syst 24:37–51
12. Rajasulochana P, Preethy V (2016) Comparison on efficiency of various techniques in treatment of waste and sewage water – a comprehensive review. Resour Technol 2:175–1842. https://doi.org/10.1016/j.reffit.2016.09.004
13. Gargano JW, Adam EA, Collier SA, Fullerton KE, Feinman SJ, Beach MJ (2017) Mortality from selected diseases that can be transmitted by water – United States, 2003–2009. J Water Health 15:438–45015. https://doi.org/10.2166/wh.2017.301

14. Massoud MA, Tarhini A, Nasr JA (2009) Decentralized approaches to wastewater treatment and management: applicability in developing countries. J Environ Manag 90:652–65990. https://doi.org/10.1016/j.jenvman.2008.07.001
15. Manyuchi MM, Mbohwa C, Muzenda E (2018) Biological treatment of distillery wastewater by application of the vermifiltration technology. South African J Chem Eng 25:74–7825. https://doi.org/10.1016/j.sajce.2017.12.002
16. Narmadha D, Mary Selvam Kavitha VJ (2012) Treatment of domestic waste water using natural flocculants. Int J Life Sci Biotechnol Pharma Res 1:1–81
17. Gerba CP, Pepper IL (2009) Wastewater treatment and biosolids reuse. Environ Microbiol:503–530. https://doi.org/10.1016/B978-0-12-370519-8.00024-9
18. USEPA (US Environmental Protection Agency) (2004) Primer for municipal wastewater treatment systems. Office of Wastewater Management and Office of Water, Washington, DC
19. Giri R, Takeuchi J, Ozaki H (2006) Biodegradation of domestic wastewater under the stimulated conditions of Thailand. Water Environ J 20(3):109–202
20. Go E, Demir I (2006) Cost analysis of alternative methods for wastewater handling in small communities. J Environ Manag 79(4):357–363
21. Wilderer PA, Schreff D (2000) Decentralized and centralized wastewater management: a challenge for technology developers. Water Sci Technol 41(1):1–8
22. USEPA (US Environmental Protection Agency) (1997) Response to congress on use of onsite and decentralized wastewater treatment systems. Office of Wastewater Management and Office of Water, Washington, DC
23. Chen H, Liu Y, Ni BJ, Wang Q, Wang D, Zhang C, Li X, Zeng G (2016) Full-scale evaluation of aerobic/extended-idle regime inducing biological phosphorus removal and its integration with intermittent sand filter to treat domestic sewage discharged from highway rest area. Biochem Eng J 113:114–122113. https://doi.org/10.1016/j.bej.2016.06.002
24. Urynowicz MA, Boyle WC, Bedessem ME, Jin S (2007) Nitrogen removal in recirculating sand filter systems with upflow anaerobic components. J Environ Eng 133:464–470133. https://doi.org/10.1061/(ASCE)0733-9372(2007)133:5(464)
25. Healy MG, Rodgers M, Mulqueen J (2004) Recirculating sand filters for treatment of synthetic dairy parlor washings. J Environ Qual 33:713–71833. https://doi.org/10.2134/jeq2004.7130
26. Chamorro S, Xavier C, Hernández V, Becerra J, Vidal G (2009) Aerobic removal of stigmasterol contained in Kraft mill effluents. Electron J Biotechnol 1212. https://doi.org/10.2225/vol12-issue2-fulltext-9
27. Khazaei M, Nabizadeh R, Mahvi AH, Izanloo H, Ansari Tadi R, Gharagazloo F (2016) Nitrogen and phosphorous removal from aerated lagoon effluent using horizontal roughing filter (HRF). Desalin Water Treat 57:5425–543457. https://doi.org/10.1080/19443994.2014.1003100
28. Sukhani S, Chanakya H (2020) Passive high-rate wastewater treatment using upwelling anaerobic lagoons as an alternative to conventional systems. In: Recent trends in waste water treatment and water resource management, pp 241–248. https://doi.org/10.1007/978-981-15-0706-9_23
29. Stefanakis AI, Bardiau M, Trajano D, Couceiro F, Williams JB, Taylor H (2019) Presence of bacteria and bacteriophages in full-scale trickling filters and an aerated constructed wetland. Sci Total Environ 659:1135–1145
30. USEPA (US Environmental Protection Agency) (2002) Onsite wastewater treatment systems manual. E.P.a./625/R-00/008. Office of Water and Office of Research and Development, Washington, DC
31. Carroll S, Goonetilleke A, Thomas E, Hargreaves M, Frost R, Dawes L (2006) Integrated risk framework for onsite wastewater treatment systems. Environ Manag 38(2):286–303
32. Kaplan OB (1991) Septic systems: hand book, 2nd edn. CRC Press/Lewis Publishers
33. Wilderer PA (2005) Sustainable water management in rural and peri-urban areas: what technology do we need to meet the UN millennium development goals? Water Sci Technol 51(10):1–6
34. Tchobanoglous G, Crites R (2003) Wastewater engineering (treatment disposal reuse), 4th edn, Metcalf & Eddy, Inc, McGraw-Hill, New York

35. Brix H (1994) Use of constructed wetlands in water pollution control: historical development, present status and future perspective. Water Sci Technol 30(8):209–223
36. Burkhard R, Deletic A, Graig A (2000) Techniques for water and wastewater management: a review of techniques and their integration in planning. Urban Water 2:197–221
37. Reed SC, Crites RW, Middlebrooks JE (1995) Natural systems for waste management and treatment, 2nd edn. McGraw-Hill, New York
38. Zhang D, Gersberg RM, Keat TS (2009) Review constructed wetlands in China. J Ecol Eng 35:1367–1378
39. Elfanssi S (2019) Étude du fonctionnement de la station de traitement des eaux usées par la technologie des filtres plantés hybride en vue de leur réutilisation en agriculture dans la zone de Tidili (province du Haouz). PhD thesis
40. Saidi A, Elamrani B, Amraoui F (2014) Establishment of a set for the treatment of wastewater from a Hammam filter and reuse in irrigation of a united farm in suburban of Casablanca. J Mater Environ Sci 5:2184–2190
41. SEEE, State Secretariat at the Ministry of Energy (2007) Mines, water and environment, in charge of water and environment – Kingdom of Morocco. Water quality standards for irrigation 2007. http://www.eau-tensift.net/fileadmin/user_files/pdf/publications/3_Irrigation.pdf
42. El Hamouri B, Nazih J, Lahjouj J (2007) Subsurface-horizontal flow construted wetland for sewage treatment under Moroccan climate conditions. Desalinition 215:153–158
43. Taouraout A, Chahlaoui A, Belghyti D, Taha I, Ouarrak K, Sammoudi R (2019) Hydraulic load rates effect on the performance of horizontal multi-soil-layering to treat domestic wastewater in rural areas of Morocco. J Mater Environ Sci 10(5):422–430
44. El Ghadraoui A, Ouazzani N, Ahmali A, El Hakim EL, Mansour T, Aziz F, Hejjaj A, Del Bubba M, Mandi L (2020) Treatment of olive mill and municipal wastewater mixture by pilot scale vertical flow constructed wetland. Desalin Water Treat 198:126–139
45. El Ghadraoui A, Ouazzani N, Saf C, Ahmali A, Aziz F, Hejjaj A, Del Bubba M, Mandi L (2021) Behavior of physicochemical and microbiological characteristics of vertical flow constructed wetland substrate after treating a mixture of urban and olive mill wastewaters. Environ Sci Poll Res. https://doi.org/10.1007/s11356-021-14874-7
46. Bruzzoniti MC, Rivoira L, Castiglioni M, El Ghadraoui A, Ahmali A, El Mansour TEH, Mandi L, Ouazzani N, Del Bubba M (2020) Extraction of polycyclic aromatic hydrocarbons and polychlorinated biphenyls from urban and olive mill wastewaters intended for reuse in agricultural irrigation. J AOAC Int 103:382–391103. https://doi.org/10.5740/jaoacint.19-0257
47. Ahmali A, Mandi L, Loutfi K, El Ghadraoui A, El Mansour TE, El Kerroumi A, Hejjaj A, Del Bubba M, Ouazzani N (2020) Agro-physiological responses of Koroneiki olive trees (Olea europaea L.) irrigated by crude and treated mixture of olive mill and urban wastewaters. Sci Hortic (Amsterdam) 263263. https://doi.org/10.1016/j.scienta.2019.109101
48. Tiglyene S, Mandi L, Jaouad A (2005) Removal of chromium from tannery wastewater by vertical infiltration reed beds. Rev des Sci l'Eau 18:177–19818. https://doi.org/10.7202/705555ar
49. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504. S0045653519313074. https://doi.org/10.1016/j.chemosphere.2019.06.081

Chapter 7
Vertical Flow Constructed Wetlands for Horticulture Wastewater Treatment Under a Hot Climate in Ethiopia

Frank van Dien

Abstract One of the largest rose nurseries in the world has been constructed in Ethiopia under a hot climate with several dry months annually. In that facility, all generated wastewater is solely treated with constructed wetlands. The effluent is not being discharged into the environment but mixed with the irrigation water of the farm, leading to Zero Liquid Discharge. The process of coming to this state of development started with a series of pilot constructed wetlands and research was carried out on the influent and effluent quality by accredited laboratories. The final report of this research was only published after a review by the Dutch National Institute for Public Health and Environment (RIVM). Many different parties were involved in this project such as a.o. DLG, Alterra (WUR), ECOFYT, the Embassy of the Kingdom of the Netherlands, and HoAREC&N. After the pilot implementation and study, the concept was upscaled and applied to the entire farm. In total, 69 constructed wetlands were built for the entire 550 ha of farm greenhouses. The removal of nutrients, metals, and the chemical residues was high, not only in terms of concentration levels, but also in the total number of residues.

Keywords Constructed wetlands · Sustainable farming · Zero liquid discharge · Ethiopian roses · Horticulture wastewater · Water reuse · Ethiopia · Hot climate

7.1 Introduction

In the past, the commercial cultivation of roses was carried out in moderate climates but in the last decades, the majority of the production has moved to the tropics. Especially in South America and Africa, there are several locations where roses are grown, mostly for the European market. The most important parameters for the development of this type of horticulture are: climate, light intensity, and the low cost

F. van Dien (✉)
ECOFYT, Boxtel, The Netherlands
e-mail: Frankv@nDien.nl

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_7

of labor. Growing roses is a very labor-intensive agricultural activity due to harvesting, selecting at length, bunching, but also crop control for plant condition, checking for bugs, moths, and of course trimming and weeding. Growers in the North of Europe faced really hard times when both costs of labor, as well as the cost of energy, became higher. Roses are not productive in forming flowers when the temperatures are too low. Hence, they are grown in greenhouses that need to be heated when temperatures drop below a certain level.

In the middle of Ethiopia, the company Sher Ethiopia PLC ('Sher') runs the world's largest rose nursery. The climate at this location is fairly hot but not really arid; daily temperatures of 25 °C or more are typical, and the annual rainfall is around 775 mm [1]. The precipitation, however, does not come equally divided over the year, hence there are a few months in which it is just hot and dry. The nursery was built in the vicinity of a large freshwater lake, the Lake of Ziway (with a diagonal of ca. 30 km). The east side of the lake is not productive, because it is too mountainous. But on the west side of this lake a lot of horticulture is being practiced, tomatoes, beans, unions, leak, corn, and teff (the common Ethiopian cereal), all using water from this lake for irrigation.

Also, the growing of roses depends on this water source, for irrigation. But it is not only a matter of water intake: at a company the size of Sher, on a scale of 550 hectares of greenhouses and with around 10,000 employees, there is also wastewater production. Around 2011, Ethiopia did not really have any active form of legislation concerning wastewater, but Sher started looking at this water flow [2]. And thinking about ways to make sure that the environmental impact would – at least – be small [3]. Prior to that, the Wageningen University & Research (WUR) in the Netherlands had indicated that Constructed Wetlands (CWs) could be a viable option, but not much knowledge was yet available for this specific sort of wastewater under these tropical conditions. WUR was working together with UNESCO-IHE on this matter, and the Dutch government showed interest and gave support through its department DLG and the first ideas were developed. Around this time, the Dutch company ECOFYT was introduced through IHE, because of its practical experiences with CWs for several sorts of wastewater, and the first designs were made. This chapter presents the CW development at this large rose nursery in Ethiopia, the performance of CW systems tested and applied and the lesson learnt from the unique application.

7.2 Materials and Methods

7.2.1 Wastewater Treatment Pilot

When these first plans were approved by Sher's board of directors, the decision was made to have a pilot, in the form of four constructed wetlands (CWs), 180 m^2 in total. After the first meetings in April 2011, it became clear that there was not much data on water quantity and water quality. The specifics of that wastewater are, besides the common parameters of domestic wastewater (due to the number of people working on the farms: toilet usage, hand washing, showering for those involved in spraying), related to these crop protection agencies and fertilizers. Then there is a certain amount of 'bucket water': the harvested roses must be kept in water and to that sometimes a small amount of chlorine is added. And most of that water is refreshed when the roses go on the transport, after being kept in cold stores in the 'pack houses'. As expected, much of the water used for the plants (both for fertilizer and for crop protection) will go to the soil, so it will not be seen or treated as wastewater. But the tools used for spraying, the 'spraying carts', and the tanks in which these materials were dissolved or mixed with the spraying and irrigation water need to be cleaned after usage. This process takes place in the farms of Sher, resulting in wastewater hot spots, called 'vocoms'. A vocom consists of toilets, washing basins, showers, mixing rooms, and water storage tanks. Each vocom may serve one to three lines of greenhouses, usually stretching from 6 to 20 hectares of roses.

So, mostly based on estimations, a series of CWs was designed. The general layout of this design was: in two lines (which were one behind another, in total 2.5 km long) there were two vocoms. Each of them would get a horizontal flow CW (HFCW), called CW1 in Fig. 7.1 [4]. The substrate would be coarse sand and the system would be almost saturated in order to get an optimal Hydraulic Retention Time (HRT). Between all greenhouse lines there are ditches, needed to evacuate the storm water during the turbulent rain periods of Ethiopia's climate. These ditches were also used to let the wastewater return to the lake from which the rose farm gets its irrigation water. In the design we continued to use this ditch to transport the water from the two vocoms, only this time: after treatment in the Horizontal Flow Constructed Wetlands (HFCW). Then, together with the bucket water from the pack house at the very end of the ditch, it was collected and pumped up to treat it once more, in two parallel Vertical Flow Constructed Wetlands (VFCW). The objective was to get as much water treated as possible and to have it discharged in the lake, as clean as possible.

7.2.2 Experimental Duration and Sampling

Part of the concept of the pilot was of course a period of research. Together with the Ethiopian partner, Horn of Africa Regional Environment Centre and Network (HoA-REC&N, usually referred to as HoAREC), Alterra (a WUR related research center) and ECOFYT, research was carried out for a period of several months in 2014. For this research, the water was analyzed, both influent and effluent at several locations in the systems, throughout the farm. The nearby lab Horticoop Ethiopia did the analyses on nutrients. Their analytical standards are shown in Table 7.1.

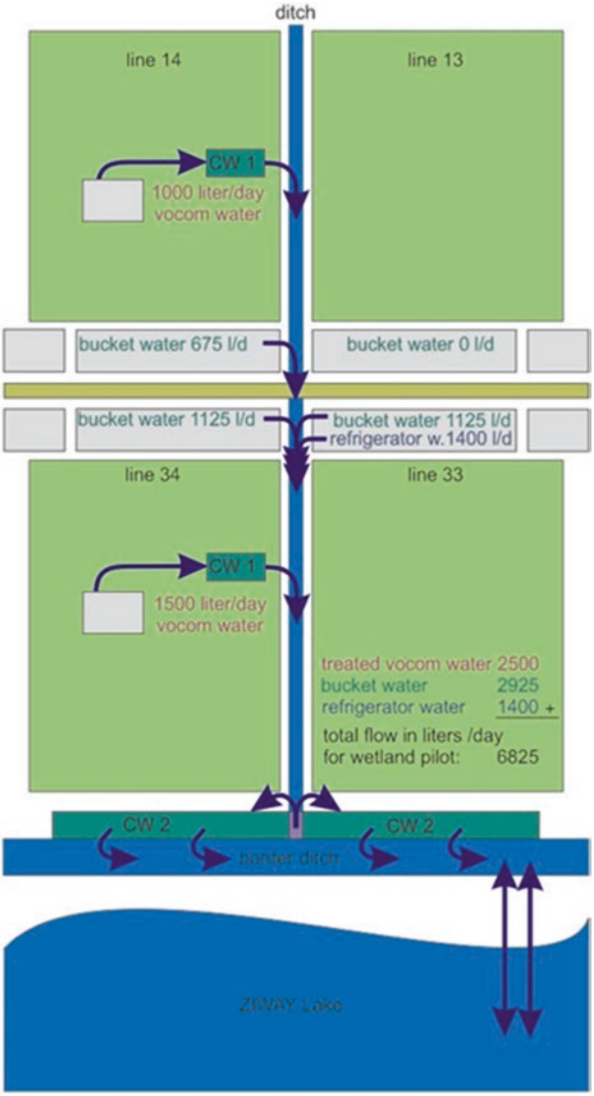


Fig. 7.1 Schematic representation of the CW pilot system

Whereas the Dutch lab Altic/Laboratorium Zeeuws-Vlaanderen did the sampling of residues of crop protecting agencies. This was done with a multi sampler, capable of detecting some 600 different residues. The analytical methods are shown in Table 7.2.

Table 7.1 Tests and examination standards used by Horticoop Ethiopia

Parameter	Examination standards
Acidity pH-H2O	ISO 10523
Conductivity EC	ISO 7888
Nitrate NO_3^-	ISO 7890-1
Ammonium NH_4^+	ISO 7150-1
Chloride cl^-	ISO 9297
Bicarbonate HCO_3^-	ISO 9963-2
Boron (B), calcium (ca), copper (cu), iron (Fe), potassium (K), magnesium (mg), manganese (Mn), molybdenum (Mo), sodium (Na), phosphorus (P), Sulphur (S), silicon (Si) and zinc (Zn).	ISO 11885

Table 7.2 Tests and examination standards Altic/ Laboratorium Zeeuw-Vlaanderen

Sample pre-treatment: In house method	Extraction with dichloromethane and petroleum ether (WVS-062)
GC-MSMS in-house method	Gas chromatography – mass spectrometry (WVS-063)
LC-MSMS in-house method	Liquid chromatography – mass spectrometry (WVS-064)
GC-ECD in-house method	Gas chromatography – electron capture detection

7.2.3 Starting Up the Wastewater Treatment Process

The research related to the pilot systems would not only result in achieved effluent data but would also reveal the influent values. And perhaps it would also lead to more insight into the daily flows of wastewater. There are no water meters at the farm, surface water is just pumped when needed. But first, these four CWs would have to be built. Being retrofitted in existing greenhouses, there was a challenge: the site was not accessible for an excavator, nor for trucks with the needed sand, so everything was brought in with donkey carts (Fig. 7.2). And all the digging (and filling) was done by hand.

A minimal impact on the environment was the intention. And next: if this was to be a successful method, the technical staff would have to be trained to expand this system throughout the company. In the beginning, the board of Sher was rather skeptical about a low-tech, natural treatment system being a possible solution for their wastewater problems. They expected that far more advanced, technical equipment was what they would need. The financial proposition for the pilot project setup was: engineering and research funded by the Dutch government, materials, and labor financed by Sher. This stimulated the board of directors of Sher and thus, in October 2012, DLG and ECOFYT ended up in Ethiopia working shoulder to shoulder with Sher's technical staff and laborers, so building and educating went hand in hand.

Fig. 7.2 Building of the first wetland, donkeys at the vocom. (Photo: ECOFYT ©)

The groundworks of the four pilot systems were prepared by Sher, according to the design drawings and in 1 week, the four systems were built, filled, and set to work.

Working with the local people was a true pleasure, though of course, they had no idea where the construction would lead to. The entire nearby city has no communal wastewater treatment plant and the concept of actually treating wastewater instead of discharging it out of sight (e.g., in soak-away pits) was an unknown concept to them.

Next, it took a period for the systems to stabilize, and to solve some minor start-up hiccups such as ensuring that the timers that regulate the pumps were resistant to the varying electrical current, the frequent electrical surges, and fallouts. Because of this, the initial digital timers were replaced with more robust analog timers. Then, in November 2012 water samples were taken periodically and sent to a lab in Ethiopia. This lab, however, had limited possibilities in the variety of parameters. It was not until August 2014 that the research took a serious form. HoAREC, an autonomous unit within the Addis Ababa University, was commissioned by the Embassy of the Kingdom of the Netherlands (EKN) to supervise the research. From week 29 to 41, 2014, water samples were taken at various fixed spots in the system, which were then analyzed in the mentioned accredited laboratories, partly in Ethiopia and partly in the Netherlands. Samples were also taken from a reference drainage ditch to make a comparison with water that is not treated by constructed wetlands. The results of these water samples have been processed by ECOFYT to calculate the efficiency of the system. Before publishing the final report, the report concept and findings were assessed by the RIVM (National Institute for Public Health and Environment in the Netherlands) who took up the role of an independent expert.

7.3 Results

From the analysis of Horticoop not all parameters are equally important from a water purification point of view. In particular, calcium, magnesium, sodium, silica, and bicarbonate do not play a role as a parameter in wastewater treatment. Potassium, boron and sulphate only play a role when they appear in high concentrations (there are, e.g., no discharge standards), but the nutrients (nitrogen and phosphorus) and metals from this set are of importance.

The parameters studied have been divided into several groups and the average final results, (percentage removal from the treated water), when comparing the most polluted influent (Vocoms) with final effluent, are as shown in Tables 7.3, 7.4, 7.5, and 7.6 [4].

Table 7.3 Pollutant reduction of various pollutants groups in the pilot CWs

Parameter	Removal performance
Nutrients	99.4% (ammonium and nitrate nitrogen, phosphorous)
Metals	94% (Magn., iron, manganese, zinc, boron, copper, molybdenum)
Heavy metals	93% (manganese, zinc, boron, copper, molybdenum)
Residues (weight)	99.96% (total weight, µg/l found in influent [5929] and effluent [9.58]).
Residues (numbers)	64% (total no. of substances found in influent [77] & effluent [28])

Table 7.4 N, P influent and effluent values and removal rates by Horticoop Lab (n = 10)

Parameter	pH	NH_4-N	NO_3-N		P
Influent vocom CW (mg/L)	6.7	20.5	348		17.2
Effluent vocom CW (mg/L)	7.5	2.7	597		2.78
Influent end CW (mg/L)	8.8	0.3	7.3	<	0.03
Effluent end CW (mg/L)	7.9	0.2	3.0	<	0.01
Total removal %		99%	99%		99.9%

Table 7.5 Residues throughout the system by Altic Lab, n = 4 (2 for infl. end), voc = vocom wetland, end = end wetlands

Parameter	Infl. vocom	Effl. vocom	Infl. end	Effl. end
Total residues found per location	77	71	32	28
Removal (%) in number of substances		8%	54.9%	63.64%
Total (µg/L) of residue per location	26,198	4467	33	10
Total removal (%) in weight in pilot		83%	99.3%	99.96%
Total removal % (µg/L)		93.6%	97.0%	100.0%

Table 7.6 Fate of some of the residues throughout the system (Altic Lab)

Parameter	Infl. vocom	Effl. vocom	Infl. end	Effl. end	Reference ditch
Fluopyram	3150	92.3	15	0.16	16
Pyrimethanil	7850	43.5	0	0.03	0
Thiamethoxam	68	570	6	1.14	2.6

When comparing the reference ditch with the final effluent of the CW, there is a significant reduction in the total residual weight (from 47.55 μg/L to 9.58 μg/L, respectively), which amounts to a removal of 79% of residual weight in the wastewater. This final calculation is, however, of a more hypothetical nature because the flows in the drainage ditches are approximated. The value would be only accurate if both ditches provide equal flow and pollution rates.

Not all residues give completely logical results like is to be seen in Table 7.3, sometimes the effluent data are higher than in the influent, related of course to the moment of usage and sampling. Some disappear in the first treatment step to reappear in the end result, for the same reason. However, the mentioned Fluopyram is a reasonable example of the fate of residues found.

The significant difference between effluent vocom and influent end wetland lies in the fact that the two CWs are up to two kilometers apart. This water is transported through the shallow ditch where the effect of UV certainly has its influence on the water composition.

7.4 Discussion

These pilots were built in order to see if CWs could provide a cost-friendly method in order to come to a minimal impact on the environment.

When the first samples were taken and the effluent as clear as in Fig. 7.3 was shown to the executive director of Sher, all initial skepticism was dropped and on the spot, he decided that the entire farm would be equipped with this system. And that the effluent should not be discharged but re-entered in the irrigation system of the farm. What was decided in that split second was consequently executed over the next years resulting in 69 CWs for the entire 550 ha of greenhouses.

From the pilot CWs we learned that:

1. Where 7 m^3/day of wastewater was expected for the pilot CWs, we now estimate it to be around 31 m^3/day, at that location. In order to keep an effective HRT, the volume of the CWs needed to be significantly bigger.
2. Solids in any wastewater are a serious threat for clogging of any purification system. Clogging may lead to many kinds of mishaps, like shortcuts in the water flow pattern to complete malfunctioning [5, 6]. Clogging does not lead to a sustainable situation. Where the initial vocom wetlands were HFCWs, the clogging occurred throughout the entire depth of the inlet zone. Restoring that was both

Fig. 7.3 CW effluent and Canna lilies. (Photo: ECOFYT ©)

time-consuming and destructive to the wetland, it meant a lot of digging. Since it was not easily possible to get more solids out of the influent water (already sedimentation tanks were installed and functional), it became clear that maintaining them became an important issue. The idea of the HFCW was dropped, in favour of the VFCW, like it was built at the end of the ditch. These wetlands, being filled with fine sand as the substrate, would not receive less suspended solids but they would accumulate over the entire surface, not *in* the substrate. And maintaining that surface appeared to be very feasible: the vegetation has to be harvested regularly, at least two times per year. And for doing so, a bed is taken out of commission for a day or two, in which the top layer dries out, giving a crust that crumbles like clay soil does when drying out. Then the plants are cut, while the crust is scooped out simultaneously.

3. Having pumps to bring all water into the wetlands and usually having parallel beds, timers regulate to which bed the water will be pumped. While we started with electronic precision timers, we learned that they are way too delicate for the electrical system of the greenhouses. The surge peaks were found to happen straight after an outage; they were produced by the diesel generators as they 'jumped in'. And these surges often 'roasted' the timers (Fig. 7.4). The timers were replaced by more robust analog ones, but they work in lump blocks of 15 minutes. That is tricky when they lose synchronicity, but they will keep on working and that matters more.
4. There was no need to experiment with a non-saturated, more aerobic substrate, the nearly saturated beds performed well, and this project was not for researching optimization of CW knowledge but for preserving the water quality and it looked like we had our bets on a winning horse, as it was. It is a bit the same with the knowledge about the water *quantity*; Installing water meters throughout the systems would be a costly adaptation, we would continue with estimates, only now supported by pulse counters and time counters per pump, per wetland. It is

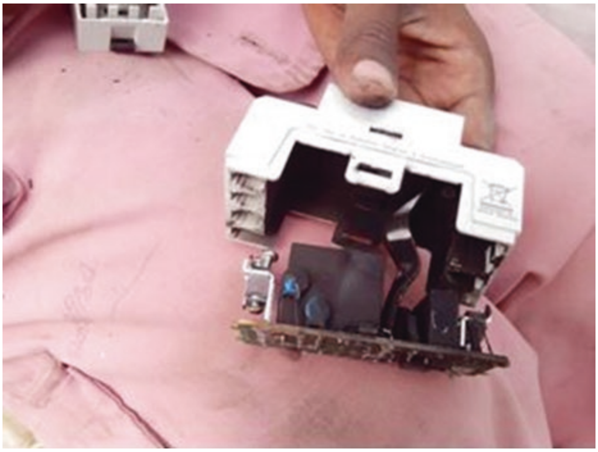


Fig. 7.4 Delicate electronics, fried when the generator jumps in after an electrical fallout. (Photo: ECOFYT ©)

a rough approach but good enough. Water meters on influent water would be adding risk to the durability and stability of the system, too.

5. Of course, we set out with looking for local vegetation; introducing exotic plant species is a 'no go' and there is no need for it, either. While we are very happy with using reed (*Phragmites australis*) in the majority of our projects, we were equally happy to find that plant in the Ziway lake. Not that abundant, but enough to harvest rhizomes (a continuously growing horizontal underground stem that puts out lateral shoots and adventitious roots at intervals.), without endangering the appearance of the plant species in any way. But it turned out that they had a meager development in the beds and that they also attracted lice sometimes, which is not appreciated in a rose greenhouse, of course. The plants that thrived best were:

   Cattails (*Typha sp.*): the local species grow really tall, 3 m easily,
   Napier grass *(Pennisetum purpureum):* initially the easiest plant to use: a piece of stem with one or two leave nodes put in the soil will do.
   Canna lilies *(Canna sp.):* the colorful and ever attractive species here grow 2 m tall and the orange/yellow flowers are bigger than a fist.

6. The first set of end wetlands (the second treatment of the combined wastewater) was set at the border ditch; "The greenhouses are for roses" was the mindset. But later, room was made inside the greenhouses for the CWs, as it was clear that the wetlands didn't conflict with the roses and the occasional weaver bird that took a wetland to build its nest was not harmful either (something no bird had or has done in the roses). And since the companies' surface was used optimally with

Fig. 7.5 View of an 'end wetland system' among the roses, at Sher Ethiopia PLC. (Photo: ECOFYT ©)

greenhouses, there was not much room for wetlands outside, like the first set, anyway. So, since the pilot, all wastewater treatment expansion is done inside the greenhouses (Fig. 7.5).

7. Where wastewater treatment was rather unknown in the region, as explained in the construction phase, there were however several institutions that showed a keen interest in the pilot and its results. Officials from the local township and drinking water company came to see the system with their own eyes. But the Ethiopian government was no less interested. They stimulated the entire horticulture branch to take an example from this project. Later even a course was initiated to introduce wetland design knowledge into the community through EHPEA's training center (the Ethiopian Horticulture Producer Exporters Association, based in Addis Abeba).
8. Maintenance of the 69 wetlands is of course mandatory. There are an equal number of pumps involved, many precipitation sumps, and almost 6500 m^2 of wetland treats more than 700 m^3 of wastewater daily. Occasional harvesting takes place (Fig. 7.6) after which the surface of the CWs can also be cleaned from the finer solids that may come with the wastewater, by scooping off a tiny top layer.

All pumps are equipped with counters both for pulses and working time and these counters are read on a weekly basis. This data is processed by ECOFYT in order to see if there are any anomalies. The three wetland managers that do the weekly check-up were trained to be proactive on the state of the systems, so they check for silt in the pump sumps and have an open eye for the functioning of the pumps. So, also if dirt blocks any pump, it is discovered promptly.

Fig. 7.6 Workmen maintain the CWs. (Photo: ECOFYT ©)

7.4.1 Opportunities and Challenges

The system is not able to treat all water in the drainage ditches year-round. There are occasionally local downpours that are so severe that it is impossible to retain that rainwater. In that case, the discharged wastewater will be very highly diluted.

In such a tropical storm event, the amount of runoff from the greenhouses is truly massive. That water has to escape freely, unhampered. The system to direct the usual daily water (including a minor rain event) to the end wetlands is simple and efficient. But once the water table in the ditches swells above a certain level, the pumps switch off and all water runs to the outer buffer canal and when that is full, to the Ziway lake and/or Awash river.

It should also be noted that the treatment system itself is a completely natural system that has been built with local materials, as well as with local plants. This provides labor and opportunities for local people whilst the result is optimal respect for the local environment and trend-setting to local environmental awareness.

Also, *after* the pilots, lessons have been learned. For example: in order to obtain a maximum water quality, we had ponds built, following the final wetlands. Those were meant to have submerged and semi-submerged water plants, like the all-over occurring water hyacinth *(Eichhornia crassipes),* to polish the effluent of the wetland beds. But it appeared that the water was too clean for them, already (water hyacinth thrives in nutritious waters), and the plants even died, lacking what they needed. Nowadays the ponds are home to Tilapia fish, who get fed a bit (Fig. 7.7).

The fish are not meant for consumption (though lab tests proved that they are of good quality and fit for consumption). Sher is into roses, not into food farming. However, from time to time the fish need to be harvested too. And Sher has donated tens of thousands of fingerlings (as young fish are called) to the Ziway lake, where fishermen have made a living on catching Tilapia for generations on end.

Fig. 7.7 The end wetlands with ponds. (Photo: ECOFYT ©)

7.5 Conclusions

Based on the evaluation report mentioned earlier, some 10 years of experience with these constructed wetlands, the close involvement of both the creators of the pilot system and the owners of the Sher wetlands, one can undoubtedly speak of a successful water treatment system under a hot climate.

The purification efficiency is high and the costs of investment, management, and maintenance are low. It goes without saying that maintenance is necessary, the system is complex enough to need constant surveying, yet it is simple enough that the essentials can be explained and transmitted to the local workers without the necessity of advanced education. A clear mind and willingness may suffice, whereas of course, a heart for the environment is a welcome bonus.

When the project started, the concept of doing anything with the used water was new. But over the years there was an entire team that had helped build the 69 wetlands, managers were appointed to keep them up and running, but more than that: it became a topic of discussion and education. Sher trained their PR staff for it as well: they would have to understand what the wetlands produced and how to communicate it to anyone interested. Many officials from government, ministries, communities, and water companies wanted to see for themselves what was going on at the Sher farm. And it changed the mindset: this would be followed up, throughout the country. The pilots finally led to raising awareness and changing legislation.

And a lot cleaner water! More than 250,000 m^3 per year are treated.

The good results of the water quality are not only due to the wetlands: Sher has, over the years, also improved on the emissions by changing from chemical crop protection to biological crop protection. It will not be possible to do so for the full 100% but Sher is striving towards the maximum possible on that front too. Hence the influent gets cleaner and it can only help maintain optimal water quality for the recycling part.

References

1. Data available at https://www.climatedata.eu/climate.php?loc=etzz0030&lang=en
2. Sustainable Trade Initiative (IDH) (2020) The adoption of constructed wetlands and biocontrol on rose farms at Lake Ziway, Ethiopia, Insight report
3. Sahle A, Potting J (2013) Environmental life cycle assessment of Ethiopian rose cultivation. Sci Total Environ 443:163–172
4. van Dien F, Boone P (2015) Evaluation report: constructed wetlands pilot at SHER Ethiopia PLC. Wageningen University & Research, ECOFYT and Alterra
5. Knowles P, Dotr G, Nivala J, Garcia J (2011) Clogging in subsurface-flow treatment wetlands: occurrence and contributing factors. Ecol Eng 37(2):99–112
6. Vymazal J (2018) Does clogging affect long-term removal of organics and suspended solids in gravel-based horizontal subsurface flow constructed wetlands? Chem Eng J 331:663–674

Chapter 8
Constructed Wetlands in a Community Setting in Mombasa, Kenya

Sarah den Haring

Abstract Constructed wetlands (CW) in the East African Region have primarily been implemented in private institutions such as hotels/lodges, individual homes, schools, flower farms and tea/coffee estates. The systems have proved to be robust, effective, and low-cost, consistently achieving the Kenyan National Environment Management Authority (NEMA) “discharge to environment” water quality standards. A CW built for a private developer serving a housing estate of 2650 people in Mombasa has also performed consistently since its construction in 2007 but has encountered a number of issues due to the unique socio-environmental context of the system in terms of management, population growth and sustainability: (1) management; the CW serves a community but no service fee is levied on the users for its operation and maintenance, (2) population growth; the area surrounding the CW has become increasingly populous since its construction causing conflict with the outside community, and (3) sustainability; illegal construction over a seasonal water course restricts all outflow from the system, including natural drainage (storm flow). This chapter aims to demonstrate that privately operated CWs can be a valuable and effective means of decentralised wastewater treatment in rapidly urbanizing areas in the tropics, but that socio-environmental factors in a community setting must be prioritized to ensure CW longevity.

Keywords Constructed wetlands · Private sector · Wastewater treatment · Decentralized wastewater treatment DEWATS · Community sewerage · Urban planning · NIMBY · Kenya · Nature-based solutions

---

S. den Haring (✉)
GreenWater Environmental Water & Sanitation Solutions, Kilifi, Kenya
e-mail: info@green-water.org; http://www.green-water.org/

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_8

8.1 Historical Context and Site Development

Sewer systems serve only 9% [1] of the Mombasa population (approximately 100,000 people), the majority of whom are located within 5 km of the Central Business District (CBD). High costs of infrastructure development and the limited financial capacity of the local water utility, Mombasa Water Supply and Sanitation Company (MOWASSCO), make centralized sewerage and wastewater treatment plant provision hard to achieve for the remaining population.

Decentralized systems therefore play an essential role in the collection and treatment of wastewater [2], especially considering an un-served population of approximately 1,100,000. Traditionally in the region, wastewater is managed using pit latrines or septic tanks followed by direct discharge to the environment, usually via a hand dug soak pit [3], a combination that achieves primary treatment but poses a risk to underlying aquifers due to discharge of only partially treated water. This is particularly serious in high-density areas where multiple soak pits result in irreversible contamination of the groundwater [4]. This may render the groundwater completely unusable for human consumption or that boreholes must be sunk to extreme depths to locate clean water [5]. Additionally, where areas are underlain by low infiltration soils such as heavy clay, these structures are ineffective and alternative treatment/disposal options are essential. The practice of constructing soak pits is not encouraged by the National Environmental Management Authority (NEMA) but many landowners are often not aware of alternative options so continue to build them [3].

A number of decentralised (onsite) wastewater treatment systems have entered the market in Kenya over the last 20 years and the compilation and subsequent enforcement of the Environmental Management and Co-ordination Act 1999 (requiring sites to comply with wastewater discharge criteria) has resulted in many sites utilising these. The systems range in technical complexity, installation cost and operational and maintenance requirements and may be broadly grouped into "underground" or "surface" installations. Underground systems are containerized (off-the-shelf) or masonry (custom built) structures, which usually incorporate a settling chamber and an active (aeration pump) or passive (high surface area media) chamber. They are often used in urban areas where space is a premium and other activities may occur very close to, or even on top of them.

Surface installations include Nature-based Solutions (NBS) such as constructed wetlands (CW) [6, 7]. The systems utilize natural processes to create different environments conducive for the removal of pollutants including biochemical degradation by microbes, adsorption and absorption to the gravel matrix, plant uptake and physical filtration [8, 9]. As nature-based systems, CWs provide a sustainable and also cost-effective solution [2], even when applied under hot or arid environments [10, 11]. A growing number of sites are now utilising CW since their value was initially identified in a system treating domestic effluent at the Carnivore Restaurant and Splash Water Park in Nairobi in 1994 [12]. CW are designed on a site by site basis and have been used successfully to treat not only domestic but also industrial, commercial and agricultural effluent in Kenya [13–17].

Despite good results achieved from CW in Kenya, there are still barriers preventing their uptake on a larger scale. GreenWater (GW), one of only two companies in Kenya with sufficient capacity to design and construct CW, reported over 15 years of operation they experienced lack of awareness of CW within water utilities as a viable option and reluctance by NEMA to approve the systems. These barriers appear to be associated with lack of information about CW.

The value of CW has, however, been recognized by private companies/individuals who collectively have built approximately 40 CW in Kenya, one of which is located in the Mombasa area. Located more than 10 km from the nearest sewer network, a housing estate to the north of Mombasa town in Kenya has three decentralized on-site wastewater treatment systems that serve a total population of more than 10,000 people. Despite the lack of wastewater regulations or municipal services during construction in the 1980s, the developer recognized the importance of making provision for the conveyance, treatment and disposal of wastewater generated by their housing. As such, areas of land at the lower end of the estate were left for the purpose of on-site wastewater treatment. The systems comprise waste stabilization ponds, oxidation ponds and a CW; each serving a distinct part of the estate.

Despite the forward thinking of the developer in respect to wastewater treatment, the social environment has significantly changed since project inception. Annual population growth in Mombasa between the years 2007–2020 was 3–3.5%, representing a population increase from 854,000 to 1.25 million. This is a little higher than the national population growth rate of 2.5% due to the enhanced movement of the population towards urban centres. This is particularly noticeable in the housing estate area, the population density of which was 2029 people/km^2 in 2009 and is projected to be 10,000 people/km^2 in 2040, almost a 500% increase [18].

Mombasa is a typical example of many cities in Less Developed Countries (LDCs) with high urbanization rates. Infrastructure services, such as sewer systems and wastewater treatment plants, are often inadequate or missing for the existing population, let alone the new arrivals. Decentralised wastewater treatment plants such as CW can therefore play a vital role in bridging the gap between private developers and public water and sanitation service providers [7], though for this arrangement to be successful in the long-term a certain enabling environment must be in place. The Mombasa housing estate that is presented in this chapter is a unique example of a CW in such a setting and over the last 14 years has highlighted a number of valuable insights, pitfalls and lessons that may be applied to comparable settings.

8.2 Materials and Methods

8.2.1 Geographical and Climatic Setting

Mombasa lies at 4.04°S 39.66°E on the south eastern Kenyan coast. It experiences a tropical monsoon climate with south westerly trade winds blowing up the coast from April to September and a north easterly wind blowing the opposite direction from October to March. The rain is distributed between two rainy seasons, the “long rains" in April to June and the "short rains" from October to November with an annual total of 997 mm. Average annual temperature is 26.1 °C with a range of 24.3–28.0 °C. A maximum temperature of 31.9 °C is experienced in February and minimum of 22.4 °C in August. Humidity is high throughout the year at an average of 77% with a variation of +/−4% [19].

8.2.2 Constructed Wetland Design and Operation

The project location is indicated in Fig. 8.1. The Mombasa CW serves the oldest part of a housing estate where quality affordable houses constructed between 20–40 years ago have now been sold to individuals or managed on a letting basis. Current house value is approximately 50,000–75,000 USD and rental value between 200–400 USD per month. The developers constructed a sewer system and septic tank for the estate, but the underlying heavy clay prevented the use of soak pits for final disposal. The result was the utilization of a series of informally operated shallow infiltration ponds to absorb and evaporate the septic tank effluent. In 2007, the ponds were failing to adequately manage (absorb) this water so GreenWater (GW), a Kenyan based CW design and construction company, was engaged to rehabilitate the system to operate correctly as a CW and improve the effluent quality to meet NEMA discharge to environment and irrigation standards.

Wastewater generated from 638 households (approximately 2338 people) in the southern part of the estate is directed to the CW system via a sewer network as shown on Fig. 8.2. A further input of water was discovered illegally connecting an additional plot comprising approximately 300 people in 73 households.

No data was available regarding volumes of wastewater entering the existing system so estimates were generated using water bills and industry average figures.

Fig. 8.1 Location of constructed wetland (CW) in Mombasa, Kenya. (Google maps 2021)

Water supply (consumption) data per capita was collected by GW through enquiries to a number of families about their water bill costs and equated to a volume based on the progressive pricing scale of the municipal water company. This gave a volume of 100 L/person/day, in line with available literature regarding peri-urban housing in developing countries [20–22]. The contributing population of 2633 people therefore consume an estimated total of 263,000 L/day (263 m^3) of which about 80% is expected enter the wastewater drainage system, a total of 210 m^3/day. This is equivalent to 1400 PE based on hydraulic loading [23].

The CW was constructed utilising the available area of approximately 10,000 m^3 and indicated on Fig. 8.2. Sewage arrives at the treatment area and enters a septic tank (volume of 350 m^3) with internal baffle walls. Settled effluent is then passed to a holding tank from where it is pumped up into the first stage of the CW. After this

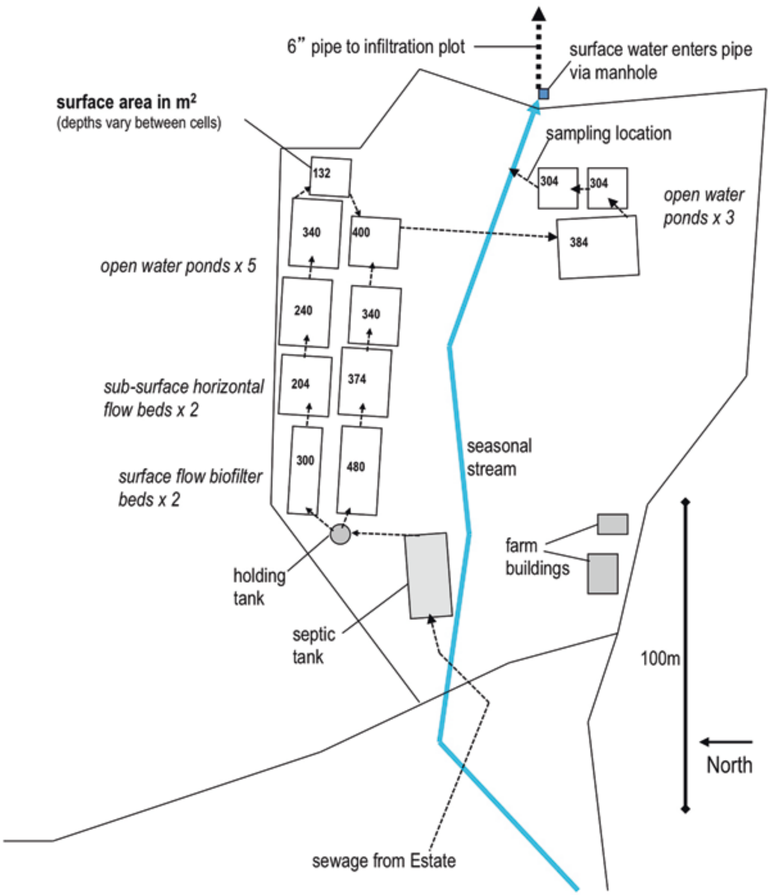


Fig. 8.2 Constructed wetland layout

point the system operates entirely by gravity. The first stage beds have been divided into two parallel sections so that water may be directed along both lines, one, or neither, depending on flow rates and maintenance requirements. The two lines join for the second stage ponds. All water passes through the following system cells:

Surface flow biofilter: rows of Vetiver grass (*Chrysopogon zizanioides*) entrap fats, oils and greases (FOG) and scum.
Sub-surface horizontal flow CW: 40 cm deep, 1–2″ washed gravel planted with Typha grass (*Typha latifolia*).
Open water ponds: 60 cm deep ponds with floating plants and Vetiver grass along margins, followed by 30 cm deep ponds to enhance UV action with planted hyacinth along margins.

The theoretical hydraulic retention time (HRT) of the system is 6.8 days. The wastewater sampling point is the outlet from the final pond prior to discharge into the seasonal watercourse as indicated on Fig. 8.2. The treated effluent has been sampled since rehabilitation in 2007 on a quarterly basis in line with NEMA requirements representing a total of 34 samples. Sampling parameters and their corresponding limits are specified by NEMA Environmental Management and Coordination, (Water Quality) Regulations 2006 as per Table 8.1. The samples were collected under ISO 5667-16:2017 and tested under the methodology detailed in Table 8.1 by this NEMA approved laboratory. The developer is responsible for all costs relating to sampling.

Intermittent municipal water supply in the estate occasionally causes water shortages, resulting in low volumes of wastewater, reduced water levels in the ponds and zero flow at the outlet. In this instance, sampling is delayed until the outlet is discharging.

Table 8.1 Water sampling parameters, limits and testing methodology

Parameter	Unit	NEMA limit	Test method
pH	pH scale	6.5–8.5	APHA 4500-H*B
Biological oxygen demand (BOD)	mg/L	30	AOAC 973.44
Chemical oxygen demand (COD)	mg/L	50	APHA 5220B
Total suspended solids (TSS)	mg/L	30	APHA 2540D
Total dissolved solids (TDS)	mg/L	1200	APHA 2540C
Total coliforms	CFU/100 mL	1000	KS 05459
Escherichia coli	CFU/100 mL	Nil	APHA 9221G
Colour	Hazen units	15	APHA 2120B
Ammonia	mg/L	100	APHA 4500 NH_3
Oil & grease	mg/L	Nil	APHA 5520C
Total phosphorus	mg/L	2	APHA 4500 P E
Copper as Cu	mg/L	1.0	APHA 3111B

8.3 Results

8.3.1 Performance Results

Effluent results for the last 5 years (a total of 13 samples) are summarised in Table 8.2 for the indicator parameters pH, BOD, COD and TSS.

The results show the CW is achieving removal efficiencies for BOD of 86%, COD of 96% and TSS of 94%. The average values of the treated effluent at the outlet are mostly within the NEMA discharge to environment levels (Environmental Management and Coordination, Water Quality Regulations 2006), the only exception to this is COD with an average outlet concentration of 54 mg/L, marginally higher than the NEMA limit of 50 mg/L. The elevated average value is due to a single sample on 14th November 2018 that had a COD of 224 mg/L and BOD of 75 mg/L, the only instance out of 13 samples where any parameters failed. A field inspection in December 2018 by GW suggested these elevated results could be as a result of surface water entering the CW from drainage failure due to solid waste blockages at a time when maintenance staff had been reduced.

The single sample failure over the five-year period indicates the CW is performing to a satisfactory level in terms of design and operation, but that continual maintenance of the CW and neighbouring area is necessary to avoid failure.

8.3.2 Operation and Maintenance of the CW

A team comprising 3–6 men is responsible for the daily management and operation of the system, maintaining the pump and plants and clearing blockages along the sewer system. This team is paid directly by the developer. A local Non-Governmental Organisation (NGO) lends support on an occasional basis with 2 or 3 people for large jobs such as clearing surface channels of solid waste or removing large areas of biomass from the treatment systems. Activities for the regular maintenance team include:

- Monthly plant trimming (wetland plants around pond margins)
- Quarterly plant removal (floating plants in ponds)

Table 8.2 Water sampling results (average values)

Parameter	Unit	NEMA limit	Inlet (aver.)	Outlet (aver.)	Standard deviation (n = 13)	Min-Max	Removal %
pH	–	6.5–8.5	7.67	7.5	0.6	6.8–8.1	n/a
BOD	mg/L	30	146	20	13	6–75	86
COD	mg/L	50	1500	54	25	16–224	96
TSS	mg/L	30	225	13.2	4.5	6–21.6	94

Note: *n/a* not applicable

- Bi-annual trimming of plants in gravel bed
- Ensuring unrestricted flow of wastewater through network into treatment systems (fixing blockages and broken pipes)
- Ensuring unrestricted flow of storm water along surface drains into water courses (clearing channels and fixing pipes) and repairing inspection chambers when damaged
- Managing the pump to control inflow of settled effluent into the CW

Other costs associated with operation of the CW are the annual NEMA license fee, quarterly sampling fees, consultant advisory costs and emptying of sludge from the septic tank as detailed on Table 8.3.

In addition to running costs, the construction cost of the system must also be considered in terms of developer investment. This includes the relative value of the land (900,000 USD) and cost of rehabilitating the CW in 2007 (50,000 USD). The original construction cost was not available for inclusion in the calculation. The total investment of the developer in this CW since 2007 (land, system rehabilitation and running costs) is therefore approximately 1,160,000 USD. None of this is recovered from the residents served by the CW.

8.3.3 Management and Regulation of the CW

Societal factors governing the operation of this CW influence the long-term sustainability of the system. Whilst the CW has achieved adequate wastewater treatment since it's rehabilitation in 2007, a number of socio-environmental issues are now impacting the acceptability and viability of the system. These are underpinned by the responsibilities and relationships between the developer, the community, regulatory organisations and the County Government. The roles of these groups are considered below with respect to concerns and solutions raised regarding the CW.

Table 8.3 Monthly operation and maintenance costs for the CW in USD

Item	Details	Cost (USD)/month
Labour	Clearing drains/CW upkeep	450
Consultancy	GW oversight	75
Power	Electricity for pump	300
Effluent discharge license	NEMA	85
Water analyses	Laboratory analyses for NEMA	130
Materials	Plumbing items, maintenance equipment etc.	200
Sludge removal	Septic tank volume 350 m^3, every 5 years	98
	Total monthly cost =	*1338*

8.3.3.1 Role of the Developer

The Developer's role is not clearly defined as they have informally assumed the role of service provider of the estate by default. There have been no agreements made with the home-owners regarding the provision of drainage services (for sewage and storm water) or payments requested for these services. Should there be an issue in the system (such as a blockage), residents lodge the complaint at the developer's public office after which the maintenance team respond. There is no fee charged for this service.

The developer has no jurisdiction regarding illegal connections to their sewer line. The extent of these connections is not known but was estimated at an additional 13% of the estate load in 2007. Ongoing construction in the proximity of the sewer line since that time may have increased this figure as pressure on land is intense and space for septic tanks and soak pits limited, combined with the impermeable nature of the soil resulting in limited absorption capacity of soak pits. Building regulations are not always enforced by the City Council allowing unlicensed contractors to take a short cut by connecting to the neighbours sewer and save themselves the cost of septic tank and soak pit construction. For a 3 bedroomed home this would be approximately 1500–4000 USD [24].

8.3.3.2 Role of Authorities

The National Environment Management Authority (NEMA), the Water Resource Authority (WRA), the County Government of Mombasa and MOWASSCO are involved with the operation of any sewer and wastewater treatment plant. Their roles are detailed below.

NEMA is the regulator for all issues relating to wastewater management. NEMA issue Effluent Discharge Licenses (EDLs) to sites discharging wastewater once they have submitted an application and paid an annual fee of 1000 USD. Quarterly monitoring results must be provided and should these fall out with the Discharge to Environment standards (as stipulated in the Environmental Management and Coordination, Water Quality Regulations 2006), NEMA may issue an Improvement Order (IO). Should the IO not be adequately addressed, NEMA may then take action to close down site activities, sometimes enforced with the aid of the armed Administration Police. NEMA are also responsible for the approval of an Environmental and Social Impact Assessment (ESIA), due at project inception. The ESIA includes a review of the surrounding land use at the time and requires interviews with local residents. This CW was constructed in advance of the regulations being enacted and therefore an ESIA was not completed. To date, NEMA have been involved with the site only during issues of conflict resolution with neighbours and provide no advisory service.

WRA have the responsibility to oversee all issues in relation to water supply as provided under Sections 12 and 13 of the Water Act, 2016. These are to:

1. Formulate and enforce standards, procedures and regulations for the management and use of water resources and flood mitigation.
2. Regulate the management and use of water resources.

WRA are involved in the site from the point of view of the seasonal watercourse. This passes through the centre of the plot and is dry for approximately 6 months of the year. During the rainy season, surface water from the upstream catchment area naturally fills this channel and is directed towards the south east to the sea. A number of constructions now block this channel and prevent the free flow of water causing flooding. No solution has been achieved with this issue to date.

MOWASSCO are responsible for the provision of water and sanitation services. At this location no sanitation/sewerage services have yet been provided by them. The development of future sewerage services in the Mombasa area has been included in the MOWASSCO Master Plan [18] but this only allows for the construction of public and community toilets and septic tanks by 2030 that will not affect this location's sewer system. Drinking water is supplied via the fresh water distribution network, originating from either Mzima Springs 240 km to the north west, Tui borehole to the south, Malele Spring 50 km to the south and or Baricho Dam 105 km to the north.

The County Government of Mombasa is responsible for all aspects of land use, planning and infrastructure (roads, street lights, storm drainage and solid waste management). Urban planning is defined as: a technical and political process concerned with the development and design of land use and the built environment, including air, water, and the infrastructure passing into and out of urban areas, such as transportation, communications, and distribution networks [25]. Urban planning was not widespread in the 1980s when the estate was constructed and even now is not always fully integrated into project planning and infrastructure development in Kenya, despite advances in legislation and enforcement.

The County Government collect annual Land Rates from all home owners in the order of 10–20 USD for a typical house in the estate, irrespective of actual services provided. Some of these services such as drainage, sewerage and wastewater treatment are being provided by the developer. Whilst the developer has made requests to the Council to take responsibility for the maintenance of the sewage and wastewater treatment system, this has not occurred as the system was privately constructed and the mechanisms for handing over are not in place.

8.3.4 Barriers

A number of issues were identified by GW as impacting on the efficacy of the CW since their involvement commenced in 2007.

8.3.4.1 Operational Issues

CW operation may be compromised by irregular flow into the system. This is experienced during times of excessively high or low flows in the sewer system and power and labour availability restricting operating hours of the CW system. Faecal sludge management is also problematic for a number of reasons detailed below.

Operational issues are encountered during heavy rains. Despite the provision of surface water drainage to direct stormwater safely away from the estate, some areas inevitably experience flooding, often due to solid waste blocking drainage channels. Residents in these areas occasionally endeavor to drain the flood water from their plots by breaking open the sewer lines at nearby inspection chambers. This results in surges of flow into the CW with a reduction of HRT. Reduced HRT may result in reduced treatment despite the issue of dilution [26–28]. The maintenance team monitor the occurrence of flooding and bypassing into the sewer network and aim to discuss this with residents when fixing these areas.

Water scarcity is also often experienced at the site during the long dry season of December to March when the supply is interrupted due to reduced water levels at source. Interruptions with the municipal water supply in the estate result in very low or no flow of wastewater passing through the CW, causing the final stage shallow ponds to dry out completely and outflow to reduce to zero. This causes plants to die and impacts on the microbial population that comprise an essential component of the CW.

Issues regarding power supply have been experienced since project rehabilitation in 2007. The system is reliant on power to pump water into the first ponds. The electricity supply in this area was erratic until 2019, with users experiencing periods between a few hours and a few days without power. In addition, the pump is manually operated and the absence of a night time operator means the pump may only run from 7 am till 6 pm. Lack of power results in the water level of the holding tank rising as wastewater is no longer lifted into the CW. Once at a certain height, wastewater reaches an overflow pipe and is directed around the CW to a soak pit on the site where water slowly infiltrates, providing the flow is not of an extended duration. In 2012–14, power cuts lasting more than 3 days were experienced on a regular basis, oversaturating the soak pit and leading to a number of sewage overflows into the watercourse. Complaints were lodged with NEMA by the downstream neighbours who observed the deterioration of water quality in the surface water channel passing their properties. To address these periods of no power, the developers considered in 2014 the addition of a solar system to maintain operations. The approximate purchase and installation cost of this was 13,000 USD. Existing annual power costs to run the pump are 3600 USD meaning the system would cover its investment cost after 4 years. Retaining the existing pump and engaging a night-time operator would allow for continual operation of the pump and inflow to the CW be distributed equally across 24 hours. The developers have not had sufficient capital to invest in this initiative.

There is no provision for faecal sludge management (FSM) at the site. Sludge is generated within the septic tank and must be removed on a periodic basis, representing a high cost to the developer (approximately 6000 USD). Due to lack of revenue collected by the developer, sludge removal is not performed regularly, resulting in reduced quality effluent emanating from the septic tank as operational volume, residence time and retention of particles are reduced. Poor final effluent quality was associated with this excessive sludge build up (observed by GW) and rectified in 2014, after which the final effluent improved to within Discharge to Environment levels.

8.3.4.2 Societal Issues

A number of issues have developed from lack of successful community engagement over the last two decades, resulting in suspicion and resentment directed towards the developers. The "not in my back yard" (NIMBY) attitude has grown as the land use surrounding the CW has changed from agricultural to residential as shown in Fig. 8.3. Specifically, five complaints have been lodged with NEMA in the last 10 years by nearby residents regarding the CW, in particular to the south where residents object to treated effluent and storm water flowing through this area. These houses are downstream of the CW and outside the estate, so do not benefit from the sewer system. Some of these houses have been constructed over the seasonal waterway without the consent of the County Council and WRA, resulting in flooding during the rainy season. Many of the houses are for rent, so landlords often lodge complaints when they feel their environment has been disturbed or their house value compromised. Complaints are also lodged due to suspicion of the treated effluent as residents do not have access to the sampling results and fear an impact to their health. Other residents bordering the northern site boundary have built houses on former agricultural land adjacent to the CW and are located as close as 5 m from the ponds. These residents have raised concerns about odours and pests emanating from the CW, also submitting their complaints to NEMA.

Fig. 8.3 Comparison of the project site in 2008 (left) and 2021(right). (Google Earth Images 2008 and 2021)

8.4 Discussion

The operational and societal concerns have highlighted a number issues regarding operating a CW in a rapidly urbanizing location. In the case of the Mombasa housing estate, urban planning in the 1980s was primarily completed by the individual (the developer) and there was no mechanism to include community consultation. At this time, they received no support or input into the proposed development from other planners such as NEMA and WRA as these bodies had not yet been formed. The water utility MOWASSCO (formerly Mombasa Water and Sewerage Company) had limited legislation on sewerage, no operations in the vicinity and no capacity for supporting private wastewater treatment systems. Mombasa City Council approved engineering designs of the septic tank but did not incorporate or endorse any treatment system following the tank.

Whilst a public utility would have a procedure for citizens to lodge and resolve complaints, no such structure exists for the private developer. When environmental issues relating to the CW arise, these are all directed at the developer as they are identified as the primary service provider. The developer is not an infrastructure provider, recognized in any way by law, but has retained the responsibility of providing this service for the houses they have built. Additionally, having provided drainage for storm water and wastewater, residents usually expect the developer to also assume the roles of the municipality (currently lacking) and provide solid waste collection and other services.

In the current light of increased pressure on land from the surrounding population, the developers are currently under pressure to close the CW. The local water utility, MOWASSCO, have not indicated a main line sewer will be provided in this area within their Master Plan [18] so a decentralized system will still be required. An alternative system acceptable in a densely population area could be a contained treatment system with all treated effluent being utilized for irrigation within the site boundaries. This would result in reduced odours and zero discharge off site of treated effluent, but storm water runoff would still need access to pass along its original route.

A rotating biological contactor (RBC) system was considered in 2007 in comparison with the CW, at an installation cost of 200,000 USD with estimated electricity costs of 675 USD/month. This system comprised a settling chamber, two RBCs and a final clarifier. Due to high operational costs and specialist personnel required by the RBC, the developer decided that a CW was a more appropriate solution at this time. Despite the RBC becoming increasingly appropriate in the current environment, it is unlikely that the developer would implement an investment of this scale without financial support and a mechanism to allow revenue collection. The most viable long-term solution for the site is to continue CW operations with improved relations with the community, potentially with zero discharge of treated effluent (re-use within the site). This would be of benefit to the agricultural activities practiced within the site where a number of banana plants, flowers and fruit trees are grown. Water quality parameters in addition to those for the Discharge to

Environment guidelines must be measured to comply with NEMA Eighth Schedule (Microbiological Quality Guidelines for wastewater use in Irrigation) and Ninth Schedule (Standards for Irrigation Water).

Conflict with the community also occurs due to security and vandalism. Concrete manhole covers are often removed to retrieve and sell the internal reinforcing bar, causing danger to other residents and blockages due to disposal of solid waste into the system. In a separate part of the estate, the surrounding wall of the oxidation ponds has consistently been destroyed due to theft of the materials (blocks removed from the wall for building houses). A cast iron trunk sewer pipe crossing a small watercourse was also stolen resulting in raw sewage discharging directly into the environment. These issues have mostly been resolved with improved access and maintenance of the whole sewer system by the on-site team and a number of watchmen.

8.5 Conclusions

The CW serving the Mombasa housing estate has performed well since its construction in 2007 due to appropriate design and regular maintenance. However, a number of social, environmental and operational factors identified at this location should be considered in future CW to make the implementation of CW more sustainable and appealing to private developers.

A significant increase in the number of decentralised wastewater treatment systems in Kenya is critical to ensure “sanitation for all” as part of the Vision for Kenya 2030 and the targets of Sustainable Development Goal 6. Capital investment and operational costs for large centralized systems are often untenable for most Water Service Providers (WSPs) due to lack of funds, so smaller, decentralized systems such as CW (often for the private sector) are required. In order to achieve this, the enabling environment must be conducive to promote these systems and support the operators. Enabling factors should include all of the following points:

1. Involvement from the outset of all stakeholders, especially the surrounding community, in the planning process
2. Verification of qualified firms to build CW
3. Increased awareness and acceptance by environmental regulators of CW
4. Mechanisms to allow operators to charge fees to users or be given financial support from the Government for their service (in lieu of sewerage rates from water utility) to cover construction, operation and maintenance costs of sewerage and wastewater treatment systems.
5. Development of urban plans in low income areas
6. Adherence to urban plans (where available) including restrictions on land use change
7. Assessment of life span of CW as part of the urban plan, and replacement with containerized systems or connected to sewer line when necessary and/or possible.

References

1. WASREB, Impact Report 16, 2019/20
2. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
3. Munga M, Mwangi S, Ong'anda H, Kitheka JU, Mwaguni SM, Mdoe F, Barongo J, Massa HS, Opello G (2006) Vulnerability and pollution of groundwater in Kisauni, Mombasa. In: Xu Y, Usher B (eds) Groundwater pollution in Africa. CRC Press, London
4. Mbugua H (2016) The effect of septic tanks sewage disposal system distances on borehole water quality in Ongata Rongai, Kajiado County, Kenya. Master Thesis, University of Nairobi
5. Chakava Y, Franceys R, Parker A (2014) Private boreholes for Nairobi's urban poor: the stop-gap or the solution? Habitat Int 43:108–116
6. Stefanakis AI, Calheiros CS, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sust 1:303–318. https://doi.org/10.1007/s43615-021-00022-3
7. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Piro P, Palermo SA, Turco M, Pirouz B, Stefanakis A, Regelsberger M, Ursino N, Carvalho PN (2021) Management of Urban Waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334
8. Stefanakis AI (2020) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 503–525
9. García J, Rousseau DPL, Morató J, Lesage E, Matamoros V, Bayona JM (2010) Contaminant removal processes in subsurface-flow constructed wetlands: a review. Crit Rev Environ Sci Technol 40(7):561–661
10. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
11. Zahui FM, Ouattara J-MP, Kamagaté M, Coulibaly L, Stefanakis AI (2021) Effect of plant species on the performance and bacteria density profile in vertical flow constructed wetlands for domestic wastewater treatment in a tropical climate. Water 13(24):3485. https://doi.org/10.3390/w13243485
12. Matiru V, Waweru S (2005) Community guide to environmental issues and to the environmental management and co-ordination act, 1999: Nairobi City. Environment Liaison Centre (International), Nairobi
13. Nzengy'a DM, Wishitemi BEL (2001) The performance of constructed wetlands for, wastewater treatment: a case study of splash wetland in Nairobi Kenya. Hydrolog Proces 15(17):3239–3247
14. Mburu N, Tebitendwa SM, Rousseau DPL, van Bruggen JJA, Piet N (2013) Performance evaluation of horizontal subsurface flow–constructed wetlands for the treatment of domestic wastewater in the tropics. J Environ Eng 139(3). https://doi.org/10.1061/(ASCE)EE.1943-7870.0000636
15. Makopondo ROB, Rotich LK, Kamau CG (2020) Potential use and challenges of constructed wetlands for wastewater treatment and conservation in game lodges and resorts in Kenya. Sci World J:9184192. https://doi.org/10.1155/2020/9184192
16. Bodin H, Persson J (2012) Hydraulic performance of small free water surface constructed wetlands treating sugar factory effluent in western Kenya. Hydrol Res 43(4):476–488
17. Bundi LK, Njeru CW (2018) Use of vegetative wastewater treatment systems for counties' effluent management in Kenya. Rwanda J Eng Sci Technol Environ 1(1). https://doi.org/10.4314/rjeste.v1i1.1S

18. JICA (2015) Project for formulation of comprehensive development master plan in the Mombasa Gate City in the Republic of Kenya
19. Climate-Data Mombasa (2021). Available at https://en.climate-data.org
20. Mara DD, Alabaster GP, Pearson HW, Mills SW, Alabaster GP (1992) Waste stabilisation ponds: a viable alternative for small community treatment systems. Water Environ J 6(1):72–78
21. von Sperling M (2007) Waste stabilisation ponds, vol Volume 3. IWA Publishing, London
22. Kayombo S, Mbwette TSA, Katima JHY, Ladegaard N, Jorgensen SE (2004) Waste stabilization ponds and constructed wetlands – design manual. Joint publication by UNEP-IETC with the Danish international development agency (Danida)
23. British Water (2013) Flows and loads – 4 sizing criteria, treatment capacity for sewage treatment systems
24. Bioseptic Sewerage Systems (2021) Cost of Septic Tank Construction. Available at http://bioseptic.co.ke
25. McGill University. What is urban planning. Available at https://www.mcgill.ca/urbanplanning/planning
26. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
27. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
28. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233

Chapter 9
Performance of Constructed Wetlands in a Hot Tropical Climate: The Case of Tanzania

Jamidu H. Y. Katima, Rwaichi Minja, Anne H. Outwater, Agnes Nyomora, Wajihu Ahmada, Abdallah Zacharia, Aness S. Mahenge, and Rob Van Deun

Abstract Since 1999, the University of Dar es Salaam and partner institutions have been conducting research, mainly in Tanzania, East Africa on various topics with the main objective of developing constructed wetlands (CW) technology as a wastewater treatment system that is effective in costs, sustainability and performance. The research involved both pilot and full-scale CW and the following topics have been covered: design based on mass transfer processes and pathogen removal, substrate and macrophyte selection, coupling of CW with other treatment systems, agricultural reuse of wastewater, and wildlife habitat services. This chapter presents a summary of the results obtained from some of these studies. The results show that improved design and configuration by increasing flow velocity improves mass transfer coefficients. Novel substrates such pumice and use of indigenous macrophytes greatly improve the performance and sustainability of the treatment system.

J. H. Y. Katima (✉)
Kampala International University in Tanzania, Dar es Salaam, Tanzania
e-mail: jkatima@katima.org

R. Minja
University of Dar es Salaam, College of Engineering and Technology,
Dar es Salaam, Tanzania

A. H. Outwater · A. Zacharia
Muhimbili University of Health and Allied Sciences, Dar es Salaam, Tanzania

A. Nyomora
University of Dar es Salaam, Department of Botany, Dar es Salaam, Tanzania

W. Ahmada
Fisheries Education and Training Agency, Mbegani Campus, Bagamoyo, Tanzania

A. S. Mahenge
Ardhi University, Dar es Salaam, Tanzania

R. Van Deun
Thomas More University of Applied Sciences, Geel, Belgium
e-mail: rob.vandeun@thomasmore.be

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_9

Coupling with other treatment systems such as waste stabilization ponds can improve the overall performance. CW have the potential to remove pathogens, including helminth eggs or larvae and protozoa cysts or oocysts. Inclusion of pathogen removal in the design equation greatly improves the accuracy of the design procedure to predict the hygienic quality of the effluent. Treated effluent has acceptable quality for reuse in, for example, paddy farming. CW improve general aesthetics and support biodiversity such as birds. For this technology to continue performing sustainably, more robust operations and management programs must be in place.

Keywords Constructed wetland · Mass transfer · Pathogens removal · Helminths · Biodiversity · Wastewater treatment · Tanzania

Abbreviations and Acronyms

BOD	Biological oxygen demand
COD	Chemical oxygen demand
CSTR	Completely stirred tank reactors
CW	Constructed wetland
E	East
FC	Faecal coliform
FWSF	Free water surface flow
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
HSSF	Horizontal subsurface flow
L	Length of constructed wetland
N	Nitrogen
NH_3^+-N	Ammonium nitrogen
NO_3^-N	Nitrite nitrogen
MORUWASA	Morogoro Water Supply and Sanitation Authority
SS	Suspended solids
SSF	Subsurface flow
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TSS	Total suspended solids
UV	Ultraviolet radiation
VSSF	Vertical subsurface flow
WSP	Waste stabilisation ponds
S	South
Sh	Sherwood number
Sc	Schmidt number
Re	Reynolds number
Pe	Peclet number

Symbols

A_s Surface area of wetland (m^2)
C_0 Inlet concentrations (mg/L)
C_e Outlet concentrations (mg/L)
d Gravel diameter (m)
d_c Diameter of aggregates (collector)
d_p Diameter of particle (pathogen), μm
D_w Diffusion coefficient (m^2/d)
g Gravitation force (N/m^2kg)
h Water column (m)
K_B Boltzmann's constant (J/K)
k_m Mass transfer coefficient (m/d)
k_r Biochemical reaction rate constant (m/d)
K_T First-order reaction rate constant (d^{-1})
Q Volumetric flow rate (m^3/d)
T Absolute temperature of wastewater (K)
u Velocity (m/s)
u_o Terminal falling velocity
W Width, m

Greek Letters

α Sticking coefficient
β Slope of a straight line
ε or n Wetland porosity
η Single media collector efficiency
η_{Gp} Collection efficiency of the wetland bottom surface
μ Dynamic viscosity of wastewater (kg/ms)
ρ Density (kg/m^3)
ρ_p Pathogen density (kg/m^3)
ρ_w Water density (kg/m^3)
ψ Ratio of relative velocity (u_r) to horizontal velocity (u_h)

9.1 Suitability of Constructed Wetlands in Hot Tropical Climates

In Tanzania, a tropical country located at −6° 22′ 22.17″ S and 34° 53′ 32.94″ E, constructed wetlands (CW) are more appropriate than mechanical systems such as trickling filters, oxidation ditches, extended aeration, membrane bioreactors and sequencing batch reactors which are relatively difficult and expensive to run and maintain [1]. CW depend on natural sources of energy, have no moving parts, and require fewer operation and maintenance costs. CW are simple, inexpensive to construct and are very efficient and sustainable. CW can be used by small communities and may be located close to the users. CW can also be used to treat difficult wastewaters such as acid mine drainage, textile wastes and to remove heavy metals and a variety of toxic compounds [2–6, 7]. Compared to most conventional technologies, CW are capable of removing a higher percentage of pathogenic organisms. CW seem to be relatively simple in engineering terms, but they are complex ecological systems capable of removing organic matter, suspended solids (SS), nitrogen compounds, phosphorus compounds, heavy metals, and pathogenic organisms. Designing high performance CW requires specific engineering skills. Combined with other treatment systems such as waste stabilization ponds (WSP), roughing filters, and septic tanks they have been shown to improve the performance of those systems [8]. However, the major limitation of CW is the requirement of large land areas.

The biological reactions involved in wastewater treatment in the CW are photosynthesis, respiration, fermentation, nitrification, denitrification and microbial phosphorus removal [9]. Photosynthesis is done by plants and algae, with the process adding carbon and oxygen to the wetland. Plants transfer oxygen to their roots, where it passes to the root zones (rhizosphere). Respiration is the oxidation of organic carbon, and is performed by all living organisms, leading to the formation of carbon dioxide and water. The microorganisms involved are bacteria, fungi, algae and protozoa. Microorganisms are responsible for the decomposition of organic carbon in the absence of oxygen, producing energy-rich compounds such as methane, alcohol and volatile fatty acids. Specialized micro-organisms are responsible for nitrogen removal through the coupling of nitrification and denitrification reactions [10]. Maintaining optimal environmental conditions in the CW is necessary for the proper functioning of wetland organisms. These environmental conditions will differ based on the specific characteristics of the wetland: flow regime, substrate used and vegetation used.

CWs can either be of surface (free) flow (FWSF) or subsurface flow (SSF) (Figs. 9.1, 9.2, and 9.3). The type of CW chosen is influenced by such factors as treatment objectives, costs, environmental conditions, and land availability. Additionally, in tropical countries a major driving factor is the control of waterborne diseases vectors such as malaria [9]. Because of this, the majority of CWs in Tanzania are SSF CW systems.

The configuration of CW in the tropical countries with hot climates is not different from those found in temperate countries. They have a combination of different zones, namely: inlet zone, macrophyte zone, deep water zone, littoral zone and outlet zones, which perform different functions. These zones are composed of substrates with various rates of hydraulic conductivity, vegetation, a water column, invertebrate and vertebrates, as well as aerobic and anaerobic microbial population.

The inlet zone consists of an inlet structure and splitter box. These structures should guarantee a flow distribution across the full width of the wetland. The macrophyte zone can take different forms depending on the choice and combination of

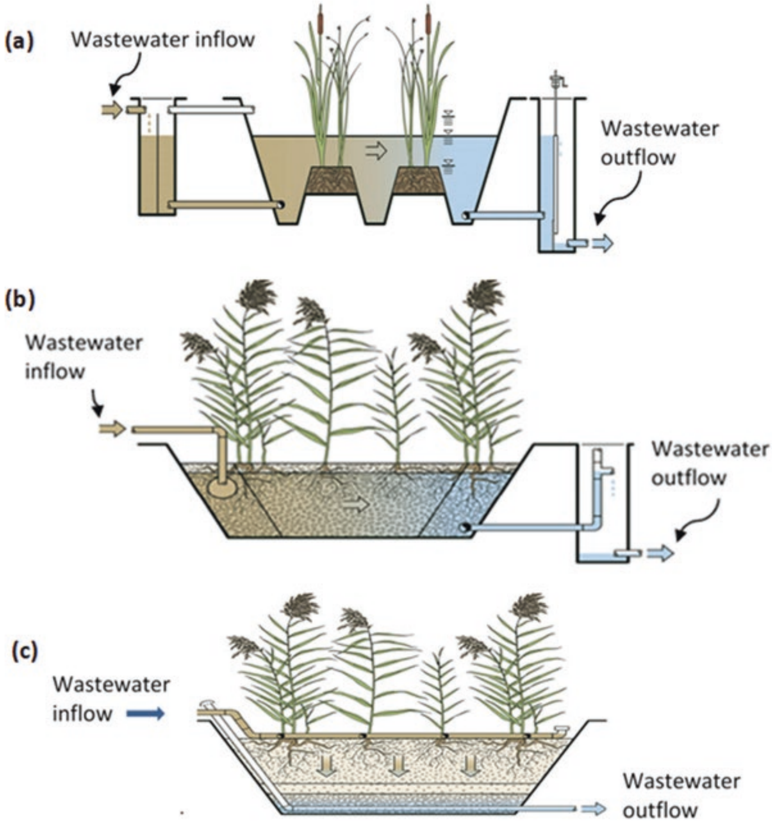


Fig. 9.1 Schematic layout of (**a**) free water surface flow (FWSF CW), (**b**) horizontal subsurface flow (HSSF CW), and (**c**) vertical subsurface flow (VSSF CW) [11–13]

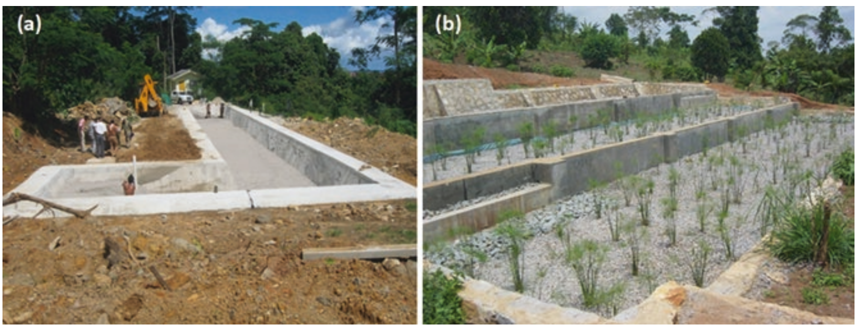


Fig. 9.2 (**a**) L-shaped CW at Mahe, Seychelles. (Photo by Karoli Njau), (**b**) sloping terrain CW at Seeta Primary School in Uganda. (Photo by Karoli Njau)

Fig. 9.3 Typical baffled HSSF CW in Tanzania. (Photo by J. Katima)

substrates, vegetation, islands, baffles and flow diversions. A substrate provides surface for the growth of a biofilm and will aid in the removal of fine particles by sedimentation or filtration. The substrate provides a suitable support for the development of extensive root and rhizome system for emergent plants.

Depending on the flow regime different types of macrophytes can be used in CW: emergent macrophytes, submerged macrophytes or free floating macrophytes. Macrophytic plants use nutrients in the water for their growth. The sub-surface zone is saturated and generally anaerobic, although excess conveyed through the plant root system supports aerobic microsites adjacent to the root and rhizomes [13, 14]. Aquatic plants have the ability to generate adventitious roots, which have the potential to extract dissolved oxygen and plant nutrients from water where gases and nutrients may be more available than in anoxic soil zones [15]. The roots aid in the removal of particulate pollutants including pathogenic organisms through physical contacts, filtration and excreted biocides [14, 16]. The stems and roots of the plants provide the surface area for the attachment of microorganisms, which are responsible for treating wastewater. These activities stimulate both decomposition of organic matter and growth of nitrifying bacteria. Plants also provide the shade, detritus for carbon and energy. Elements like baffles, islands and flow diversions are incorporated to improve the hydraulic efficiency of the CW. A non-vegetated deep-water zone will reduce short circuiting by re-orienting the flow path.

Open water can be used as sedimentation zone and can offer better oxygen transfer as well as pathogen die off through UV radiation. Moreover, these zones will provide habitat for waterfowl. In the littoral zone the vegetation protects embankments from erosion. The outlet zone consists of collection devices, spillway, weir and outlet structures. These elements collect the effluent without creating dead zones in the wetland. Special structures control the depth of the water column in the wetland and provide access for sampling and flow monitoring [10].

The available land and terrain may dictate the layout of the CW as depicted in Fig. 9.2. Such configurations require due consideration of the hydraulic efficiency and the application of the Darcy equation in the calculation of the maximum flow rate.

9.2 The Tanzanian Experience

9.2.1 Mass Transfer, Velocity-Based Design

The breakdown of pollutants in an HSSF CW is a combination of two processes. First, the pollutants must be transported from the wastewater to the biofilm that has formed on the substrate and rhizomes. Subsequently, these pollutants are broken down in the biofilm through biochemical processes. Generally, the reaction rate of these biochemical processes is measured by calculating the temperature-dependent first-order reaction rate constant (K_T). The transport is governed by molecular diffusion as a result of a concentration gradient present, whereby the diffusing component moves from a place of high concentration to one of low concentration. The efficiency of this process is measured by the mass transfer coefficient (k_m), which is influenced by the flow velocity. Higher velocities giving more turbulence, which reduces the possibility of forming a boundary film of standing water that causes a lesser concentration gradient and thus complicates the diffusion process. The flow velocity within a HSSF CW depends on the flow rate, water depth, length to width ratio and porosity of the substrate used. Njau et al. [17] tested the use of baffled systems (Fig. 9.3) and controlling the hydraulic loading rate to attain higher velocities. They found that velocity improves mass transfer coefficients. Their conclusion was that incorporation of mass transfer into CW design procedures improves the performance of CW systems and reduces the land requirements.

Most design equations are developed in temperate climates, using site-specific or regional-specific data. Such equations when applied in tropical climates, without modification, either oversize or undersize the system, due to differences in hydrology and climate. The following modified design equations were found suitable for designing HSSF CW in Tanzania. A modification of the design equation used the dimensionless groups, Sherwood number (Sh) (Eq. 9.1), Schmidt number (Sc) (Eq. 9.2) and Reynolds number (Re) (Eq. 9.3) to correlate mass transfer coefficients with velocity.

$$Sh = \frac{k_m d}{D_w} \tag{9.1}$$

$$Sc = \frac{\mu}{\rho D_w} \tag{9.2}$$

$$\mathrm{Re} = \frac{\rho u d}{\mu} \tag{9.3}$$

Where k_m = mass transfer coefficient (m/d), d = gravel diameter (m), μ = viscosity of wastewater (kg/ms), D_w = diffusion coefficient (m^2/d), ρ = density (kg/m^3), u = superficial velocity (m/d).

The Sherwood number is the function of Schmidt number and the Reynolds number [18] as expressed in Eq. (9.4).

$$\frac{k_m d}{D_w} = C \cdot \left(\frac{\mu}{\rho D_w}\right)^{\alpha} \left(\frac{\rho d u}{\mu}\right)^{\beta} \tag{9.4}$$

From Eq. (9.4), the values of ρ, μ, C, d and D_w, are constant at a fixed temperature thus, Eq. (9.4) can be expressed as:

$$k_m = C' u^{\beta} \tag{9.5}$$

The mass transfer coefficient, k_m in Eq. (9.5) is related to the temperature-dependent volumetric first-order reaction rate constant (K_T) obtained in the design equation of HSSF CW that assumes plug flow characteristics (Eq. 9.6). K_T is obtained directly by plugging in the values of inlet and outlet concentrations for BOD_5, NH_3^+-N, NO_3^--N and TKN to Eq. (9.6).

$$A_s = Q \frac{\left(\ln C_0 - \ln C_e\right)}{K_T h \varepsilon} \tag{9.6}$$

Where A_s = surface area of wetland (m^2), C_0 and C_e are inlet and outlet concentrations (mg/L), h = water depth (m), Q = volumetric flow rate (m^3/d) and ε = wetland porosity (fraction).

The observed values of K_T can be partitioned into the mass transfer coefficient k_m and the biochemical reaction rate constant k_r as follows:

$$\frac{1}{K_\mathrm{T}} = \frac{1}{k_\mathrm{r}} + \frac{1}{k_\mathrm{m}} \tag{9.7}$$

If $k_m = k_r$, the system will be mass transfer controlled [19, 20]. Therefore, the velocity will determine the overall reaction rate. From Eq. (9.5), the ln – ln plots of velocity and mass transfer coefficients can be produced, and the linear regression analysis gives a slope β and intercept ln(C′). Table 9.1 summarizes the research results.

There is a significant relationship between velocity and removal rate constants for BOD_5, NO_3^--N, NH_3^+-N and TKN for domestic wastewater. Higher velocities of wastewater moving through the HSSF CW have been observed to bring about higher pollutant removal rates. Thus, the performance of HSSF CW depends on the mass

Table 9.1 C′ and β calculated from ln – ln plots of velocity and mass transfer coefficients for different types of pollutants. (R^2 = determination coefficient of linear regression, n = number of samples)

	C′	β	R^2	n
BOD^5	0.12	0.87	0.904	24
NH_3^+-N (ln(u) ≤ 2.4 m/d)	0.004	1	1	4
NH_3^+-N (ln(u) > 2.4 m/d)	0.051	0.81	0.583	18
NO_3^--N	0.170	1.20	0.918	22
TKN	0.048	0.94	0.9022	19

transfer processes and the rate constant for different wastewater parameters depends on velocity according to the equation of the form $k_m = C'u^\beta$.

Increasing the flow velocity to obtain a better mass transfer coefficient can be achieved by increasing the length to width ratio, for example by the introduction of baffles. However, this can lead to two problems. First, the smaller cross-sectional area can lead to overland flow for a given flow rate (Darcy equation). Second, the supply of contaminants at a smaller cross-sectional area will place a high load on the HSSF CW in the inlet zone, which can cause clogging. An important possible application of HSSF CW in tropical regions is the polishing of effluent from waste stabilization ponds. These effluents are characterized by high flow rates, but low concentrations of pollutants. In such conditions, the removal processes in HSSF CW are likely to be governed by mass transfer limitation as a result of the low concentration gradient. In another study, the removal rates in HSSF CW treating WSP effluent were optimized by increasing the interstitial velocity in the system [21]. A pilot installation of various HSSF CW that work as completely stirred tank reactors (CSTR) was set up to test the effect of different interstitial velocities in a controlled environment.

The interstitial velocity can be calculated using Eq. (9.8) and the removal rate constants are calculated from Eq. (9.9).

$$u_i = \frac{Q}{W.h.\varepsilon} \tag{9.8}$$

Where u_i is interstitial velocity (m/d), Q is the flow rate (m^3/d), W is the width of the HSSF (m), h is the water depth in the HSSF (m), ε is the porosity (decimal fraction).

$$C_e = \frac{C_0}{(1 + k.HRT)} \tag{9.9}$$

Where C_e is the outlet concentration (mg/L), C_0 is the inlet concentration (mg/L), k is the overall removal rate constant (d^{-1}), HRT is the hydraulic retention time (d).

The research results showed that, at low flow velocities, the diffusion process is the limiting process. Increasing the interstitial velocity up to a value of 36 m/d, significantly improved the removal rate constants for COD removal. Above this value, the reaction rate of the biochemical processes in the biofilm becomes the limiting factor. It was concluded that optimizing the configuration of HSSF based on the ideal interstitial velocity, avoiding overland flow through application of the Darcy formula, would result in a reduction of the necessary surface area with approximately 40% [21].

9.2.2 Modified Design Equation for the Pathogen Removal in a HSSF CW

Nutrient removal is always a key driving factor in temperate countries, while in the tropics, removal of pathogenic organisms has a high priority. The majority of existing design equations do not include pathogen removal. The processes involved in pathogen removal include filtration, adsorption and sedimentation. On the design aspect, the processes are affected by the design geometry (length to width ratio, total substrate surface area) and operational factors like hydraulic retention time as shown in Fig. 9.4 [22].

The design equation which was developed is derived from Eq. (9.10).

$$\ln\left(\frac{C}{C_o}\right) = -\left[\frac{3}{2}\frac{\alpha\eta\psi\left(1-n\right)}{nd_c} + \frac{\alpha\eta_{Gp}\psi}{h}\right]L \quad (9.10)$$

Where C_0 and C are inlet and outlet concentrations of pathogens in wastewater stream, α is the sticking coefficient, *n* is the bed porosity, η_{Gp} is the collection efficiency of the wetland bottom surface, ψ is the ratio of relative to horizontal velocity($\frac{u_r}{u_h}$), η is the single media collector efficiency, d_c is the diameter of aggregates(collector), *L* is the length of the CW and *h* is the water column in the CW.

From Eq. (9.11) the following symbols are given as [21].

$$\Psi = \frac{u_r}{u_h} = \sqrt{\left(\frac{\rho_w}{\rho_w+\rho_p}\right)^2 + \left[\left(\frac{\rho_p}{\rho_w+\rho_p}\right)\frac{u_o}{u_h}\right]^2} \quad (9.11)$$

Where ρ_p and ρ_w are densities of pathogens and water respectively and u_o is the terminal falling velocity of pathogen.

$$\eta = \eta_D + \eta_I + \eta_G \quad (9.12)$$

η_D, η_I and η_G are theoretical values for single collector when the transport mechanisms are by diffusion, interception and settling respectively. They are given as,

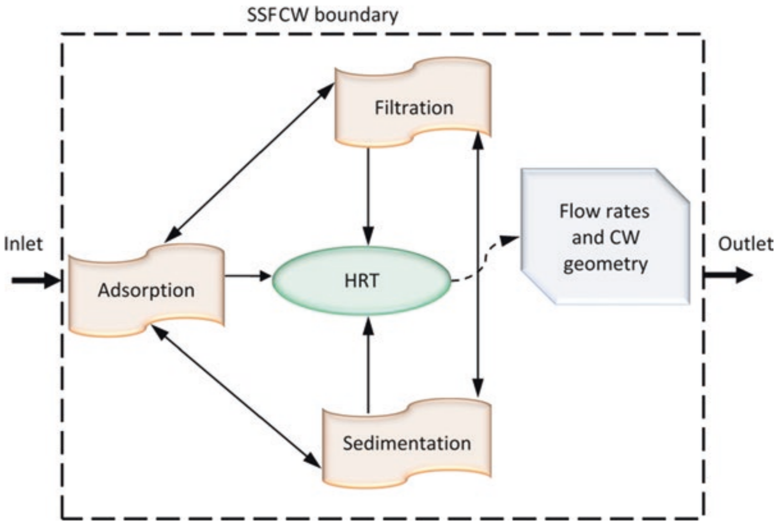


Fig. 9.4 Conceptual diagram of pathogens removal [22]. The arrow direction shows from where the factor is enhanced (HRT = Hydraulic Retention Time)

$$\eta_D = 4.04\mathrm{Pe}^{-2/3} = 0.9\left(\frac{K_B T}{\mu d_c d_P u_h}\right)^{2/3} \tag{9.13}$$

$$\eta_I = \frac{3}{2}\left(\frac{d_P}{d_c}\right)^2 \tag{9.14}$$

$$\eta_G = \left(\frac{(\rho_P - \rho_w) g d_P^{\ 2}}{18\mu u_h}\right) \tag{9.15}$$

Where Pe is the Peclet number, p_d is the pathogens diameter, μ is the dynamic viscosity of wastewater, g is the gravitation force, K_B is the Boltzmann's constant and T is the absolute temperature of wastewater.

To correct the discrepancies that exist between model and observation, the addition of porosity term is required [23, 24]. Therefore;

$$\eta_D = 4.04 B^{1/3}\mathrm{Pe}^{-2/3} = 0.9 B^{1/3}\left(\frac{K_B T}{\mu d_c d_P u_h}\right)^{2/3} \tag{9.16}$$

Factor B is related to the bed porosity with the following expression

$$B = \frac{2\left(1-\gamma^5\right)}{2-3\gamma+3\gamma^5-2\gamma^6} \tag{9.17}$$

Where, $\gamma = \left(1-n\right)^{1/3}$ and n is the bed porosity.

Substituting Eqs. (9.15), (9.16) and (9.17) into Eq. (9.10) then the total collector efficiency become:

$$\eta = 0.9B^{1/3}\left(\frac{K_B T}{\mu d_c d_P u_h}\right)^{2/3} + \frac{3}{2}\left(\frac{d_P}{d_c}\right)^2 + \left(\frac{\left(\rho_P-\rho_w\right) g d_P{}^2}{18\mu u_h}\right) \tag{9.18}$$

The value of η_{Gp} in Eq. (9.19) is given as (Table 9.2):

$$\eta_{Gp} = \frac{u_o}{u_r} = \frac{u_o}{\psi u_h} \tag{9.19}$$

After insertion of the data above the model in Eq. (9.10) yields Eq. (9.20).

$$C = C_0 e^{-0.23644L} \tag{9.20}$$

The equation was validated by correlating with the regression model (Eq. 9.21) generated from experimental data.

Table 9.2 Parameters used in the CW design equation

Coefficient	Range	unit	Source
Boltzman constant (K_B)	1.38×10^{-23}	J/K	[23]
Diameter of faecal coliform (d_p)	1	μm	[25]
Density of water (ρ_w) at 28 °C	996.2	Kg/m^3	[26]
Viscosity of water (μ) at 28 °C	8.324×10^{-4}	Pa.s	[26]
Density of faecal coliform (ρ_p)	1050	Kg/m^3	[23]
Porosity of aggregates (n)	0.40	–	From field study
Pore velocity (u_h)	1.8	m/day	From field study
Average diameter of collector (d_c)	0.02	m	From field study
Sticking coefficient (α) for parasites and bacteria	1	–	[27]
Wetland depth, (h)	0.6	m	From field study
Influent concentration of faecal coliform (C_0) for domestic wastewater	1×10^7	CFU/100 ml	[10]

$$FC = \ln\left(\frac{FCo}{FCi}\right) \quad (9.21)$$

Whereby FC = transformed log unit of faecal coliform (CFU/100 ml), L = length (m). Both coefficients for intercept and length were significant (p = 0.000 and $R^2 = 0.91$). Substituting the length of HSSF in Eqs. (9.20) and (9.21) can be deduce to [22]:

$$\ln\left(\frac{FC}{FCo}\right) = -0.23644L \quad (9.22)$$

9.2.3 Choice of Macrophytes

CW vegetation (macrophytes) plays a vital role in the remediation of water by supporting and participating in the physical, chemical and microbiological processes that occur [28]. Choice of suitable plants is a critical step.

There is a variety of macrophytes in the tropical climate, as such the choice of the plants should be based on the diversity of physical and chemical niches present in wetlands. Plants indigenous to the same ecological zone as the CW should be used.

Mangroves have been found to be suitable for specific applications because of their unique characteristics including (1) tolerance of extreme environmental conditions such as high salinity, extreme tides, high temperatures and muddy, shifting anaerobic/aerobic soils substrate [29]; (2) high potential as a biomass sink for nutrients; (3) tolerance of periodically inundated water conditions; (4) aerial roots and oxygen translocation systems that make them highly adapted to growth in anoxic muds. Two mangrove species *Rhizophora* and *Avicenia marina*, have been used to treat wastewater from beach hotels near Dar es Salaam (Fig. 9.5). A*vicenia marina* performed better in reduction of all pollutants from domestic wastewater than *Rhizophora* [30].

The plants which are commonly used for CW include *Cyperus papyrus, C. dubis, Kyllinga erectus, Phragmites mauritianus, Typha domingensis* and *T. capensis*. In one study, *K. erectus* was found to perform better than the rest in most pollutant removal. However, *P. mauritianus* establishes well and has a long growing period (Fig. 9.6). As such, the majority of CW constructed in Tanzania have used *P. mauritianus* that is abundant in eastern and southern Africa [31].

9.2.4 Wetland Substrates and Soils

The substrate is one of the most important components of the wastewater treatment in the wetland. There is abundant literature on the role of soils in CW [10, 32, 33]. The microbiological (e.g., bacteria and fungi), chemical (e.g., iron oxides) and

Fig. 9.5 Mangroves planted in a free water surface flow CW in Dar es Salaam, Tanzania. (Photo by Mahenge)

Fig. 9.6 *Phragmites mauritianus* in a 3-home CW in Dar es Salaam, 3 years after planting. (Photo by A. H. Outwater)

physical (e.g., high silt and clay content) nature of substrate make many systems function as efficient 'sinks, filters, or transformers' of nutrients, particularly phosphorus, nitrogen and carbon [34]. Heavy metals are efficiently trapped by processes of direct adsorption, complexing with organic matter and the formation of insoluble sulphides in the sediments, and through the formation of iron-plaques on the roots of trees [35].

In Tanzania, clogging has been found to be a common phenomenon that can occur in SSF CW, thus reducing the efficiency of the system. Gravel is often favored in Tanzania because of the greater ease and uniformity with which the effluent can flow through, and its availability. However removal of pollutants by a substrate also depends on its porosity, surface area, surface physical chemical properties and pH [36]. Other indigenous substrates including pumice, limestone, granite [37, 38], are abundantly available in Tanzania.

Pumice has been especially studied. Pumice has about 3.5 times pore surface area and about 4.5 times pore volume compared to granite [37]; due to its porosity, it has a large surface. Its physicochemical properties, give it good potential as substrate and catalyst support [39]. Minja and Ebina [40] studied removal of arsenic from water using pumice and Masatsuchi soil (weathered granite soil) of which pumice had more surface area but Masatsuchi sand performed better at various pH. Removal of arsenic by pumice was pH and arsenic speciation (As(V) or As(III)) dependent [41]. The performance of pumice on removal of phosphate may be attributed to the availability of elements Al, Ca, Fe and Mg which are good for phosphate adsorption [36, 37]. Pumice was found suitable to treat pollutants in wastewater and landfill leachate [37, 39, 41].

9.2.5 Coupling the CW with Other Treatment Systems

CW systems can be used as a single standing wastewater treatment system or coupled into a larger treatment system. The latter is the most widely used option in Tanzania. In such an integrated system, CW may be used for secondary treatment of wastewater or for polishing (tertiary treatment) [8]. In Tanzania, integration of CW to other wastewater treatment systems was observed to improve the wastewater effluent quality. Table 9.3 shows typical improvements in wastewater treatment for different configurations.

Table 9.3 Improved parameters of coupled wastewater treatment systems in Tanzania

Primary and/or secondary system	Type of	Parameter	Percentage improvement	Reference
Up-flow anaerobic sludge blanket reactor	Horizontal subsurface flow	BOD (mg/L)	45%	[42]
		COD (mg/L)	62%	
		TSS (mg/L)	76.7%	
Full-scale waste stabilization pond	Free water surface flow	Helminths (eggs/L)	NA (helminths were removed completely)	[42, 43]
		Protozoa (oo) cysts/L	NA (protozoa were completely removed	
		FC (log unit/100 ml)	16%	
Full-scale waste stabilization pond	Horizontal subsurface flow	FC (CFU/100 ml)	31.9%	[43, 44]
		TDS (mg/L)	1.8%	
Anaerobic and facultative ponds	Horizontal subsurface flow	Helminths (eggs)	61.5%	[45]

9.2.6 Volarisation of Treated Wastewater

It is well recognized that compared to rain-fed agriculture, irrigation boosts crop production 3–4 times [45]. Water for irrigation can either be sourced from bodies of fresh water or from reuse of effluent from aquaculture or aquaponics, and wastewater treatment systems.

Effluents from CW contain essential elements, like carbon, nitrogen and phosphorus and trace elements vital for plant growth such as zinc, copper and boron which, if not used, are lost in a futile process that causes over-fertilization (eutrophication) of water bodies and the oceans. Integrating CW effluent with agriculture can cheaply recover these nutrients (as fertilizer) for usage in agricultural production systems. For example, in aquaculture, fish excrete nitrogenous waste products dissolved in their urine and faeces. These together with feed derived waste undergoing decomposition dissolved in aquaculture are appropriate for reuse in plants as well as sequestration to avoid ammonia and nitrite toxicity in the environments.

Irrigation using effluent provides double benefit; water and fertilizer. In Tanzania, typically ammonia nitrogen in raw domestic/municipal wastewater range from 26.3–35.3 mg/L, while nitrate concentration in effluents (treated wastewater) ranges from 11.30–11.44 mg/L. The influent and effluent of CW averages have been estimated at 30.8 ± 4.5 mg/L and 11.37 ± 0.07 mg/L, respectively. Phosphorus concentration in raw domestic/municipal wastewater ranges from 18.1–56.5 mg/L, whereas phosphorus concentration in effluents ranges from 6.72–39.9 mg/L. The influent and effluent averages from CW have been estimated at 50.5 ± 6.0 mg/L and 29.0 ± 6.0 mg/L, respectively; thus, making the treated effluent from CW to be "eco-friendly" alternative to conventional irrigation which supplies only pure water [10, 46]. In Morogoro Tanzania, Nyomora [46] compared the effects on rice cultivation of using tapwater, wastewater, and a combination of wastewater and NPK (nitrogen, phosphorous, potassium) fertilizer found that the wastewater that had passed through a fish pond was the most effective means of increasing rice yields.

9.2.7 Improvement of Wildlife Habitat

Living creatures are also an important part of the effectiveness of CW. For example, in mangrove forests, the muddy or sandy sediments are home to a variety of invertebrates, and microorganisms who are participating in breaking down detritus into nutrients.

CW have been shown to be important habitats for reptiles, amphibians and birds around the world [47]. A meta-analysis of 186 natural wetlands and CW found that CW had a significantly higher biodiversity than natural wetlands (0.05) [48]. They are so effective that a highly damaged wetland from excessive agricultural off-take, was successfully rejuvenated by Ducks Unlimited Canada using municipal sewage with the primary objective to restore habitat for native waterfowl [49]. In Tanzania also, CW support wildlife.

Richness, abundance and diversity of birds increase with wetland area [47], but even small wetlands can harbor a surprising amount of diversity. In Tanzania, a CW merely 3 x 1 meter in size, planted with *Phragmites mauritianus* in urban Dar es Salaam (DSM) provided a case study [50]. Until the 1990's, this Mikocheni area of DSM was a large coastal natural wetland of which only remnants are left. *P. mauritianus* is still found alongside the several small rivers running through DSM to the Indian Ocean. As shown in the Table 9.4 below, the CW planted with *P. mauritianus* provided a natural environment which attracted and supported displaced native fauna.

Biodiversity was increased in a manner compatible with urban living. Moreover, since CW are odorless, the system itself served as an attractive, interesting, vertical green element in the overall garden design.

At the municipal sewage treatment plant in Morogoro where a CW was coupled with sewage treatment ponds, ten granivorous passerine species (including weavers, quelea, bishops, and widowbirds) were recorded [45]. One species, Southern Red Bishop Birds, were found nesting in the CW planted with *P. mauritianus*. At this site the CW was about 80 m from farmers' fields. Bishop birds were recorded eating paddy and maize crops. To protect the crops, the farmers hired somebody to chase the birds away from 5 AM to 7 PM. Therefore, although the birds of the two nests

Table 9.4 Wildlife found in a residential constructed wetland in urban Dar es Salaam, Tanzania

Species name	Native Habitat	Habitat used	Comment
Birds			
Zanzibar red bishop	Coastal Kenya and Tanzania	Breeding, nesting, raising young.	Has been permanently displaced from most of DSM by destruction of original wetlands.
Speckled Mousebird, purple-banded sunbirds, scarlet-chested sunbirds, Grey-headed sparrows, spectacled weaver, African Golden weaver, black-headed weaver, red-billed Firefinch, blue-capped cordon bleu, bronze Mannikin, yellow-fronted canary, green-backed Cameroptera,	Various parts of East Africa, including coast	Safe resting places, temporary shelter, nesting materials,	Endemic only to East Africa, except for the latter, which is also found in southern Africa.
Reptiles			
Yellow-headed dwarf gecko	Narrow coastal strip from S. Kenya to N. Mozambique	Resident	Globally rare. Locally common.
Pemba speckle-lipped skink	Pemba and coastal Tanzania	Dry season	The color is bright bronze.
Amphibians			
Marbled snout-burrower	Eastern Africa	Rainy season resident, mating, laying eggs,	Globally unusual. Locally fairly common.

in the CW were only a small percentage of the passerines feeding in the agricultural fields, it can be seen that passerines nesting amongst the *P. mauritianus* reeds, would be detrimental to nearby farmers' crops. In certain circumstances it is beneficial to nearby farmers if passerine nests found in the CW, are periodically removed early in the nesting cycle.

In Tanzania, CW planted with the native *P. mauritianus* have increased diversity of indigenous flora and fauna in both urban and rural areas. Those who are constructing wetlands should consider that the habitat may have a significant role in supporting and rejuvenating local biodiversity.

9.3 Conclusions

Constructed wetlands are exciting and effective wastewater treatment technologies, particularly in tropical countries such as Tanzania where the warm climate supports the growth of microorganisms responsible for treatment. Different studies in Tanzania has shown that design equations developed in temperate climates, need to be adjusted to take into account the hydrology and temperature dependence of macriobial functioning. It has also been found that inclusion of pathogen removal improves the performance of CW in removing pathogens, which are have significant impact on human health and volirisation of treated wastewater in the tropical climate. Innovation on how to configure the CW, e.g. introduction of baffles improve mass transfer coefficient and reduces the size of the CW for a given treatment task. Furthermore, the terrain will determine the configuration of the CW; however, functional parameters such as the slope should be maintained, in whatever configuration. Studies have shown that treated wastewater can be used for irrigation, thereby reducing the application of inorganic fertilizers. In addition, CW habitat increase local biodiversity. Continued research into, particularly is the design equations will improve the performance of CW, this in turn will make the CW technology more attractive as a primary treatment technology in the tropical countries.

References

1. Baumann P, Krauth KH, Maier W, Roth M (2012) Operational problems in wastewater treatment plants. Practice guideline troubleshooting and correction of operational problems. ISBN 978-3-88721-371-8
2. Pat-Espadas AM, Loredo Portales R, Amabilis-Sosa LE, Gómez G, Vidal G (2018) Review of constructed wetlands for acid mine drainage treatment. Water 10(11):1685. https://doi.org/10.3390/w10111685
3. Shehzadi M, Afzal M, Khan MU, Islam E, Mobin A, Anwar S, Khan QM (2014) Enhanced degradation of textile effluent in constructed wetland system using *Typha domingensis* and textile effluent-degrading endophytic bacteria. Water Resour 58:152–159

4. Khan S, Ahmad I, Shah MT, Rehman S, Khaliq A (2009) Use of constructed wetland for the removal of heavy metals from industrial wastewater. J Environ Manag 90 (11:3451–3457
5. Mozaffari MH, Shafiepour E, Mirbagheri SA, Rakhshandehroo G, Wallace S, Stefanakis AI (2021) Hydraulic characterization and removal of metals and nutrients in an aerated horizontal subsurface flow "racetrack" wetland treating oil industry effluent. Water Res 200:117220
6. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
7. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504. S0045653519313074. https://doi.org/10.1016/j.chemosphere.2019.06.081
8. Kimwaga RJ, Mashauri DA, Mbwette TSA, Katima JHY, Jørgensen SE (2004) Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania. Phys Chem Earth Parts A/B/C 29(15–18):1243–1251
9. Chakraborti RK, Bays JS (2020) Natural treatment of high-strength reverse osmosis concentrate by constructed wetlands for reclaimed water use. Water 12(1):158. https://doi.org/10.3390/w12010158
10. Kayombo S, Mbwette TSA, Katima JHY, Ladegaard N, Jorgensen SE (2004). Waste stabilization ponds and constructed wetlands design manual. Dar Es Salaam/Copenhagen: United Nations environmental program – international environmental technology Centre (UNEP-IETC) and Danish international development agency (Danida)
11. Walton WE (2012) Design and management of free water surface constructed wetlands to minimize mosquito production. Wetl Ecol Manag 20:173–195
12. Vymazal J, Kröpfelová L (2008) In: Anderson CI, Christensen TH (eds) Wastewater treatment in constructed wetlands with horizontal sub-surface flow: environmental pollution, vol. 14. Springer Science, Czech Republic
13. Dotro G, Langergraber G, Molle P, Nivala J, Puigagut J, Stein O, von Sperling M (2017) In: Techset N (ed) Treatment wetlands, biological wastewater treatment series. IWA Publishing, London, UK
14. Gerba CP, Thurston JA, Falabi JA, Watt PM, Karpiscak MM (1999) Optimazoation of artificial wetland design for removal of indicator microorganisms and pathogenic protozoa. Water Sci Technol 40(5):365–368
15. Su YM, Lin YF, Jing SR, Hou PCL (2011) Plant growth and the performance of mangrove wetland microcosms for mariculture effluent depuration. Mar Pollut Bull 62(7):1455–1463
16. Mburu N, Thumbi GM, Mayabi AO (2008) Removal of bacterial pathogens from domestic wastewater in a tropical subsurface horizontal flow constructed wetland. In: Sengupta M, Dalwani R (eds) Proceedings of Taal 2007: the 12th World Lake Conference, pp 1010–1015
17. Njau KN, Gastory L, Eshton B, Katima JHY, Minja RJA, Kimwaga R, Shaaban M (2011) Effect of diffusional mass transfer on the performance of horizontal subsurface flow constructed wetlands in tropical climate conditions. Water Sci Technol 63(12):3039–3045
18. Rajeshwar K, Ibanez JG (1997) Environmental electrochemistry. Academic Press. ISBN-13: 978-0125762601
19. Njau KN (1998) Electrochemical treatment of diluted process water from a galvanic plant. PhD Thesis, Technical University Eindhoven, Eindhoven, The Netherlands
20. Fogler HS (1999) Elements of chemical reaction engineering. Prentice Hall of India, New Delhi
21. Rugaika AM, Kajunguri D, Van Deun R, Van der Bruggen B, Njau KN (2018) Mass transfer approach and the designing of horizontal subsurface flow constructed wetland systems treating waste stabilisation pond effluent. Water Sci Technol 78(12):2018
22. Wajihu A (2019) Pathogens removal from wastewater using sustainable treatment wetlands. Master Thesis. University of Dar es Salaam

23. Mayo AW (2003) Kinetics of bacterial mortality in granular bed wetlands. 4th WaterNet/Warfsa symposium: water, science technology and policy convergence and action by all, 4(15–17), pp 1–6
24. Khatiwada NR, Polprasert C (1999) Kinetics of fecal coliform removal in constructed wetlands. Water Sci Technol 40(3):109–116
25. Bartram J, Balance R (1996) Water quality monitoring – a practical guide to the design and implementation of freshwater quality studies and monitoring programmes. UNEP/WHO ISBN 0 419 22320 7 (Hbk) 0 419 21730 4 (Pbk)
26. Paar A (2018) Viscosity of water – viscosity table and viscosity chart. [online]. Available: https://wiki.anton-paar.com/en/water/. Accessed 31 Oct 2018
27. Yao K-M, Habibian MT, O'Melia CR (1971) Water and wastewater filtration: concepts and applications. Environ Sci Technol 5(11):1105–1112
28. Chazarenc F, Merlin G, Gonthier Y (2003) Hydrodynamics of horizontal subsurface flow constructed wetlands. J Ecol Eng 21:165–173
29. Mahenge A (2015) Nitrogen transformation and removal in horizontal surface flow constructed mangroves wetland. Huria J Open Univ Tanzania 19(1):36–55
30. Pamba S (2008) The potential use of mangrove constructed wetland for domestic waste water treatment. MSc. dissertation, University of Dar es Salaam
31. Outwater AH, Locker I, Gereau RE (2019) A garden guide to coastal east African plants. Mkuki na Nyota Publishers, Dar es Salaam
32. Katima JHY (2005) Constructed wetlands: a chemical engineering perspective, professorial inaugural lecture series, No. 47. University of Dar es Salaam, Tanzania
33. Debusk WF, Reddy KR (2005) Litter decomposition and nutrient dynamics in a phosphorus enriched everglades marsh. Biogeochemistry 75:217–240
34. Boonsong K, Patanapolpaiboon P (2002) Usage of mangroves in constructed wetlands municipal wastewater treatment system. In: Mbwette TSA, Katima JHY, Kayombo S, Pratap HB (eds) Proceedings from 8th international conference on wetland systems for pollution control, vol. 2. Arusha – Tanzania, pp 952–960
35. Ye Y, Tam N, Wong Y (2001) Livestock wastewater treatment by a mangrove pot-cultivation system and the effect of salinity on the nutrient removal efficiency. Mar Pollut Bull 42:513–521
36. Drizo A, Frost CA, Grace MJ, Smith KA (1999) Physico-chemical screening of phosphate removing substrates for use in constructed wetland systems. Water Res 33(17):3595–3602
37. Njau KN, Minja RJA, Katima JHY (2003) Pumice soil: a potential wetland for treatment of domestic wastewater. Water Sci Technol 48(5):85–92
38. Kimwaga RJ, Mashauri DA, Mbwette TSA, Katima JH, Jørgensen SE (2004) Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania. Phys Chem Earth Parts A/B/C 29(15–18):1243–1251
39. Mdoe JEP, Minja RJA, Daniel L (2012) Wet oxidation of maleic acid by a pumice supported copper (ii) shiff base catalyst. Tanzania J Sci 38(2):28–38
40. Minja RJA, Ebina T (2002) Arsenic adsorption capabilities of soil-bentonite mixtures as buffer materials for landfills. Clay Sci 12(1):41–47
41. Ebina T, Minja RJA, Wakui Y, Chaterjee A, Onodera Y, Stucky GD (2003) Synthesis and arsenic adsorption capability of Smectite-titanium oxide nanocomposite of tunable pore size. Clay Sci 12(2):85–89
42. Paschal C, Gastory L, Katima JHY, Njau KK (2017) Application of up-flow anaerobic sludge blanket reactor integrated with constructed wetland for treatment of banana winery effluent. Water Pract Technol 12(3):667–674
43. Zacharia A (2020) Efficiency of selected natural wastewater treatment systems for removal of parasites and their operational factors in Tanzania. MSc thesis, Muhimbili University of Health and Allied Sciences, Dar es Salaam, Tanzania
44. Kihila J, Mtei K, Njau KN (2014) Wastewater treatment for reuse in urban agriculture; the case of Moshi municipality, Tanzania. Phys Chem Earth Parts A/B/C 72–75:104–110. https://doi.org/10.1016/j.pce.2014.10.004

45. Katima J, Outwater AH, Pamba S (2017) Integrating constructed wetlands technology with urban agriculture and fish farming for improved agricultural productivity through use of recycled wastewater. https://doi.org/10.13140/RG.2.2.12582.32328
46. Nyomora AMS (2015) Effect of treated domestic wastewater as source of irrigation water and nutrients on rice performance in Morogoro. Tanzania J Environ Waste Manag 2(2):47–55
47. Hsu CB, Hsieh HL, Yang L, Wu SH, Chang JS, Hsiao SC, Su HC, Yeh CH, Ho YS, Lin HJ (2011) Biodiversity of constructed wetlands for wastewater treatment. Ecol Eng 37(10):1533–1545
48. Ghermandi A, Van Den Bergh JC, Brander LM, De Groot HL, Nunes PA (2010) Values of natural and human-made wetlands: a meta-analysis. Water Resour Res 46(12):W12516. https://doi.org/10.1029/2010WR009071
49. White JS, Bayley SE (1999) Restoration of a Canadian prairie wetland with agricultural and municipal wastewater. Environ Manag 24(1):25–37
50. Outwater AH (2012) Subsurface flow constructed wetlands as wildlife habitat: a case study in Dar Es Salaam, Tanzania. International water association. Water Pollut Contr Newslett 40:20–24

Chapter 10
Constructed Wetlands Lessons from Three Middle East Countries : The Effect of Plants and Filter Media on CW Performance

Hassan Azaizeh, Abeer Albalawneh, Samer Kalbouneh, and Yoram Gerchman

Abstract Water scarcity is an on-going issue in the Middle East region, and wastewater treatment and reuse could relieve much of this water scarcity. This is currently done in most of Israel and partially in Jordan and Palestine, but mostly in large centralized wastewater treatment facilities, making the dissemination of wastewater reuse in the rural areas of the region complicated. This chapter describes the building, testing and adaptation of constructed wetlands in Israel, Jordan and Palestine. We describe and discuss different types of CWs, the use of different media, and the importance of plants vs water loss through transpiration. We also describe the maturation process of the CWs. The results suggest that CWs can indeed offer an effective way to aleviate water scarcity and improve agriculture production in the rural areas in the Middle East.

H. Azaizeh
Institute of Applied Research, Affiliated with the University of Haifa, The Galilee Society, Shefa-Amr, Israel

Tel Hai Academic College, Department of Environmental Science, Upper Galilee, Israel

Department of Natural Resources & Environment Managment, University of Haifa, Haifa, Israel

A. Albalawneh
Director of Environment and Climate Change Directorate, National Agricultural Research Center (NARC), Albaqaa, Jordan

S. Kalbouneh
Water and Wastewater Treatment and Reuse Department, Biodiversity and Environmental Research Center (BERC), Nablus, Palestine

Y. Gerchman (✉)
Oranim Academic College, Tivon, Israel

Department of Evolutionary and Environmental Biology, University of Haifa, Haifa, Israel

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_10

Keywords Constructed wetlands · Middle East · Wastewater treatment · Reuse · Rural areas · Media · Plants · Israel · Palestine · Jordan

10.1 Introduction

The Middle East region is a semi-arid to arid area, with yearly precipitation of 435, 402 and 111 mm for Israel, Palestine and Jordan respectively [1]. The limited precipitation is accompanied by non-evenly distribution of the rain throughout the year, with most of the rainfall limited between October to April, and the July to August being practically dry (Table 10.1). This situation results in chronic water shortage in these three countries, making wastewater treatment and use in agriculture of great promise [2, 3]. In Israel, approx. 90% of the wastewater is collected and treated, and the treated wastewater (approx. 500 million m^3 yearly) is used in agriculture (as of 2016, approx. 30% of agriculture water was treated wastewater). In Jordan and Palestine, wastewater collection and treatment are lacking, mainly due to the high cost of the complex collection and treatment infrastructure, and their impracticality in rural areas (Table 10.1). Under these conditions, Constructed Wetlands (CWs) are of much interest as possible solution [4].

In this chapter we summarize our experience in constructing and utilizing CWs in Israel, Palestine and Jordan. CWs are easy and cheap to build extensive wastewater treatment 'devices'. They are built to mimic the natural process by which water are cleaned as they flow in through the stream [6, 7], and are well known with their low energy demands, operating costs, and low environmental impact [4, 8, 9]. They have been suggested for use in arid areas although such is still limited [10].

10.2 Israel

Israel is leading in wastewater collection, treatment and reuse for agricultural irrigation and aquifer recharge, with almost 90% of the wastewater collected and 85% treated and reused. As of 2016, about 30% of agricultural irrigation in Israel is done with treated wastewater, and this practice is spreading toward municipal gardening. Currently almost all of the wastewater is treated by centralized wastewater treatment plants (WWTPs), and there are 89 large (treating at least 300,000 m^3 yearly) WWTPs spread throw-out the country (data from Israeli Ministry of Environmental Protection, 2020). Furthermore, in Israel all water sources, including wastewater, are considered public property, thus, private treatment and reuse are considered illegal. As of 2020, almost all of the wastewater treatment is handled by state authorized "water corporates", each one handling different geographical region. The water corporates are responsible for selling the fresh water to the population and for collecting and treating the wastewater.

Given the above, it is not surprising that CWs are a rarity in Israel. Many of the CWs treat a single household, although a few community CWs do exist. Nevertheless,

Table 10.1 Water, land and climatic data for Israel, Jordan and Palestine

Parameter[a]	Israel	Jordan	Palestine
Land area (km^2) (2018)	21,640	88,780	6020[b]
Total population (millions) (2019 data)	9	10[c]	4.7[b]
Rural population (% of total)			c
Fresh water consumption (million cubic meter)	554.4 (2019)[d]	1100 (2015)	408
Water use per capita per day	704 (2018)[d]	75 (2019)[e]/294[e]	88.3[j]/202[e]
Agricultural land (% of total) (2016 data)	25	12	49[c]
% of agricultural land irrigated	32 (2016)	10 (2016)	5.4 (2013)[c]
% of freshwater used for agriculture	32 (2017)[d]	52 (2015)	45 (2005)
Wastewater collection (%; million cubic meter/y) comments	94[d]; 513[d] 99 large WWTPs	65% of households connected[e;] 6% in rural areas[f]; 240 (expected by 2025) 34 centeral WWTPs[g]	30% (2018); 20 Sewage connection vary between 0% of households in tubas to 59 percent in Qalqilya)[h]
Wastewater reuse (%; million cubic meter) comments	75[d]; 355[d] 31%[d] of agricultural water,	N/A, 146.7 26% of agriculture water	2%; 1.24[i]
Agriculture, forestry, and fishing, value added as % of GDP (2018)	1.1	4.9	7.4[c]

[a] [1]
[b] Including refugees
[c] For Gaza strip and West Bank together
[d] Israeli Water Authority data, available at http://www.water.gov.il/Hebrew/WaterResources/Effluents/Pages/default.aspx
[e] Aquastat – collected through https://knoema.com/
[f] Jordanian Ministry of Water and Irrigation, 2017, available at http://www.waj.gov.jo/sites/en-us/default.aspx
[g] Data adapted from Saidan et al. [5]
[h] World Bank Group. 2018. Securing Water for Development in West Bank and Gaza: Sector Note. World Bank, Washington, DC
[i] Dr. Clive Lipchin, Eng. Shira Kronich, Jaclyn Best, Wastewater in the West Bank – Report for the Knesset, Centre for Transboundary Water Management, Arava Institute for Environmental Studies, February 7th 2016
[j] Palestinian Central Bureau of Statistics presentation. Found in https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiD3vuV3MXuAhUQyaQKHcVUDPYQFjACegQIBRAC&url=https%3A%2F%2Funstats.un.org%2Funsd%2Fenvironment%2FFDES%2FEGES6%2FSession%25202_15Water%2520statistics_Palestine.pdf&usg=AOvVaw2YRV7Y7rGJXOjDrkVajUal

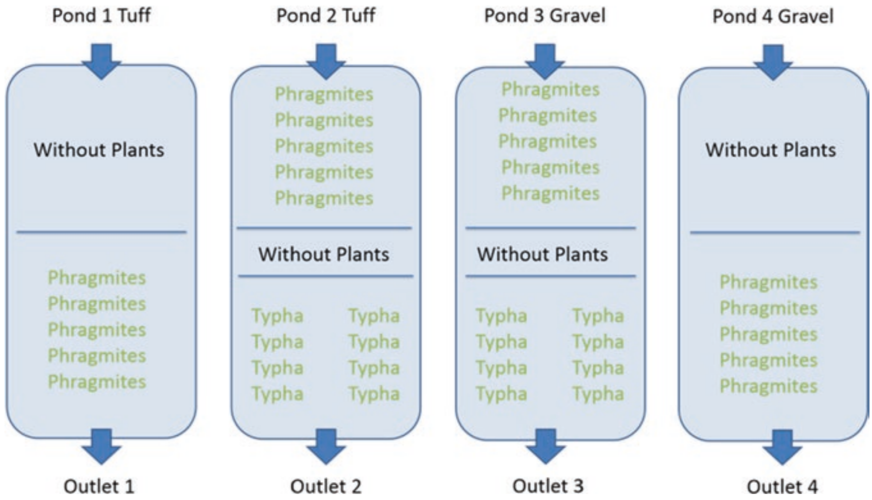


Fig. 10.1 Overview diagram of the four CWs design

since water and wastewater research is highly regarded in Israel, CWs are also an active subject of research (For recent publications see: [11–13].

Many parameters were previously shown to affect CWs efficiency, among them vegetation type and cover [14–16] and substrate size and type [9, 17]. Plants have been shown to have an effect on microbial population and activity [18], but also to cause water loss due to transpiration (up to 15% were reported, [19]). Substrate type can also affect CWs performance [20]. Nevertheless, the effect of these parameters was rarely compared on identical 'real-life' wastewater due to the complexity of such experiments.

We have designed and constructed a system of four horizontal subsurface-flow (HSSF) CWs with different characteristics in Sakhnin city near a domestic wastewater sedimentation pond site (Fig. 10.1). Primary wastewater effluents were pumped directly from the sedimentation pond and divided equally into the different CWs. All of the CWs were constructed to include two segments. While both HSSF CW1 and HSSF CW2 contained tuff as the plant growth matrix, the other two wetlands (HSSF CW3 and HSSF CW4) contained gravel. HSSF CW1 consisted of a plant-free segment followed by a *Phragmites australis*-planted one. HSSF CW2 consisted of *Phragmites australis*-planted segment followed by a *Typha angustifolia*- planted one. HSSF CW3 and HSSF CW4 were constructed exactly as the first two CWs except for gravel, which was used as the support matrix instead of tuff. Each pond was fed continuously daily with 2 m^3 of municipal wastewater after 4 h of sedimentation. The CWs were operated at an HRT of 24 h.

Inlet and outlet samples were collected from the different CWs during the winter 2016–2018 on 2 sampling events. The samples were subjected to microbiological and chemical analysis using standard methods in order to determine the quality of the treated wastewater.

10.2.1 Evaluation of CW-Effluent Chemical Quality

The microbial quality was determined by enumeration of total bacteria, fecal coliforms and *E. coli* (fecal indicators), and *Salmonella* (as a representative of pathogenic bacteria) using standard enumeration methods.

Tables 10.2 and 10.3 summarize water quality after 7, and 26 (winter) months of CW operation. As shown in Table 10.2, all CWs achieved significant reduction of most of the parameters. However, no clear differences in performance were found at this stage among the four different CWs due to the high variability in the removal values obtained for most of these parameters. Data shows that the COD was more than 100 mg/L, which is above the Inbar Israeli regulations for unlimited irrigation. Therefore, the obtained results indicate that further treatment is still required before using the effluents for unlimited irrigation. In winter (unfavorable conditions), the COD and nitrogen removal of the two Phragmites-Typha serially-planted CWs were significantly reduced (Table 10.3).

10.2.2 Evaluation of the Microbial Quality of CW-Effluent

The removal of heterotrophic bacteria (HB), fecal coliforms (FC), *E. coli* and *Salmonella*, was monitored for the different CWs for almost 3 years starting from the setup stage until maturation. During this period, the CWs were sampled primarily in summer, i.e. in favorable environmental conditions ("good performance"). In order to gain insight into the performance stability of the CWs, in the third year of operation the removal efficiency was also evaluated during winter, i.e. during unfavorable or suboptimal conditions ("bad performance").

As shown in Fig. 10.2, CW age significantly affected the removal efficiency of bacteria in all CWs, with increase from 40–70% (0.22–0.52 log; 1 month of operation) to ~95–99% (1.3–2 log) after 7 months, and remaining constant within this range for the next 21 months. The different CW showed differences through the setup stage (first 7 months), with the Tuff-*Phragmites-Typha* CW showing significantly better results. When the CW system reached maturation (i.e. after 7 months), these differences disappear, suggesting that the design (presence or absence of plants, serial plantation, and substrate type) has a pronounced effect only at the setup stage. The fact that the obtained removal rates were still within the typical removal rate range of CWs [9] suggests that further optimization or additional treatment is required for more efficient application of HSSF CWs for treatment of primary wastewater. Unexpectedly, although *Salmonella* infections are more common in summer than in winter, the majority of the summer influent and effluent wastewater samples were negative for *Salmonella* while those of the winter were positive.

Table 10.2 Average concentrations and removals of the various parameters after 7 months of CW operation

		Average concentration\removal								
		TSS (mg/l)	COD Total (mg/l)	COD soluble (mg/l)	Ammonia (mg/l)	Nitrate (mg/l)	Total Nitrogen (mg/l)	UVT (%)	pH	EC
Maximal allowed levels	Irrigation	10	100		20		25	90	6.5–85	1.4
	Discharge	10	70		1.5		10	85	7–85	
CW										
Influent sample		194 ± 120	725 ± 131	406 ± 104	67.25 ± 12	2.846 ± 0.3	70.1	5	7	1.73
Effluent samples No plants –Phragmites (Tuff) (Removal %)		19 ± 9 (90.2± 8)	102 ± 103 (85.9 ± 15)	87 ± 60 (78.57 ± 7)	45 ± 4 (33.08 ± 12)	2.41 ± 0.4 (15.3 ± 6)	47.41 (32)	28	8	1.21
Phragmites-Typha (Tuff) (Removal %)		15 ± 19 (92.26± 8)	337 ± 268 (53.5 ± 29)	240 ± 167 (40.88 ± 5.3)	63.65 ± 11 (5.35 ± 4)	1.82 ± 0.4 (36 05 ± 12)	65.47 (6.56)	28	8	1.38
No plants –Phragmites (Gravel) (Removal %)		32 ± 11 (83.5 ± 15)	246 ± 77 (66.1 ± 12)	118 ± 57 (70.93 ± 5)	42.25 ± 2 (37.17 ± 8)	1.54 ± 0.1 (45.88 ± 8)	43.79 (37.52)	25	8	1.76
Phragmites-Typha (Gravel) (Removal %)		37 ± 15 (80.92 ± 15)	158 ± 122 (78.2 ± 12)	118 ± 34 (70.93± 14)	56.5 ± 7 (15.98 ± 15)	1.69 ± 0.2 (40.61 ± 10)	58.19 (16.97)	30	8	1.78

Table 10.3 Average concentrations and removals of the various parameters after 26 months of CW operation

March, 2019		Average concentratlon\removal							
		TSS (mg/l)	COD Total (mg/l)	COD soluble (mg/l)	TKN [mg/l]	Turbldity (NTU)	UVT (%)	pH	EC
Maximal	Irrigation	10	100				90	5.5–8.5	1.4
levels	Discharge	10	70				85	7–85	
CW									
Influent sample		176 ± 4.8	682.05 ± 58	326.41 ± 28	89.66	38.2	2.5	5.91	1.568
Effluent samples									
Phragmites –No plants (Tuff) (Removal %)		2.4 ± 1.2 (98.63 ± 1)	109.62 ± 21 (83.92 ± 8.9)	95 ± 2.8 (70.89 ± 2.1)	84.08	35.7	21.9	5.8	1.242
Phragmites-Typha (Tuff) (Removal %)		1.2 ± 0.8 (99.32 ± 0.3)	153.47 ± 13 (74.50 ± 6.1)	151.02 ± 15 (53.73 ± 4.6)	95.27	57.1	30.9	5.78	1.341
No plants –*Phragmites* (G ravel) (Removal %)		2.4 ± 1.1 (98.63 ± 0.25)	136.41 ± 11 (80.01 ± 6.3)	97.44 ± 4.91 (70.14 ± 3.8)	74.83	72.6	24.5	5.81	1.43
Phragmites-Typha (Gravel) (Removal %)		16 ± 2.1 (90.91 ± 18)	202.18 ± 9 (70.34 ± 7.1)	165.65 ± 17 (49.25 ± 5.1)	95.38	67.1	27.2	5.86	1.412

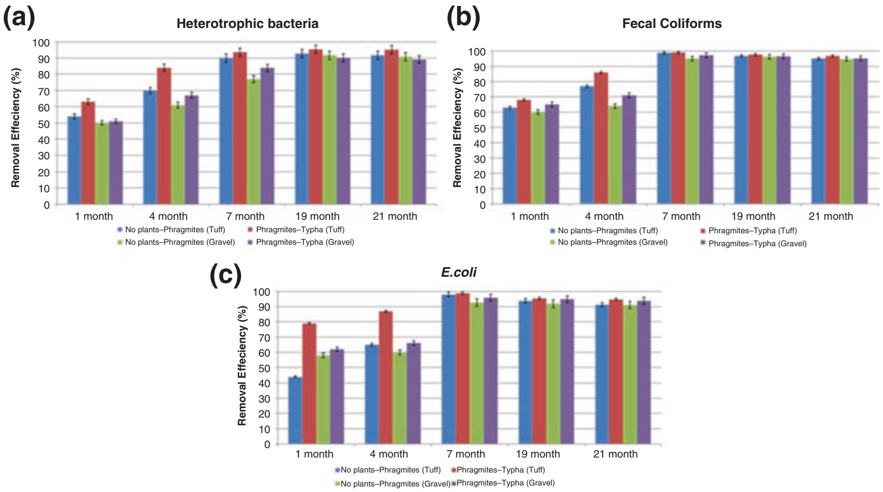


Fig. 10.2 Removal efficiencies of (**a**) heterotrophic bacteria, (**b**) fecal coliforms, and (**c**) *E. coli* as a function of the operation time

10.3 Jordan

Jordan is one of the five most water-deprived countries in the world. Jordan climate is generally arid to semi-arid, with 90% of Jordan receiving less than 200 mm rainfall per year [21]. The amount of available fresh water per capita lags far behind that of most other countries. In 2008, the renewable fresh water resources available per capita in Jordan were about 145 m^3 per year, and these are projected to fall to less than 91 m^3 per year by the year 2025; for reference, the alarm line for water scarcity is estimated at 500 m^3 per year per capita [21]. Water demand in Jordan continues to increase, and water availability for agricultural irrigation is a limiting factor for food production. Indeed, Jordan is over-pumping water, with estimated water stress (i.e., freshwater withdrawal as % of availability) of 151% [1]. Indeed, there are many regions of the country over-pumping is a reality, with up to 75% over-pumping (i.e., above the sustainable level) in Az Zarqa [22].

Much of the Jordanian population is rural (8.8%; Table 10.1), and not connected to sewage systems (Table 10.1). Given this and that much of the water is used for irrigation (Table 10.1), making wastewater reuse of high importance in Jourdan. In Jordan, the challenge of wastewater reuse is exacerbated, due to the low water use and resulting low quality greywater generated, especially in rural communities, contains high concentrations of Total Suspended Solid (TSS), Biological Oxygen Demand (BOD_5), and Chemical Oxygen Demand (COD) [23], and worldwide the highest values of EC, BOD, and total Phosphorous (P) were found in Jordanian greywater [24].

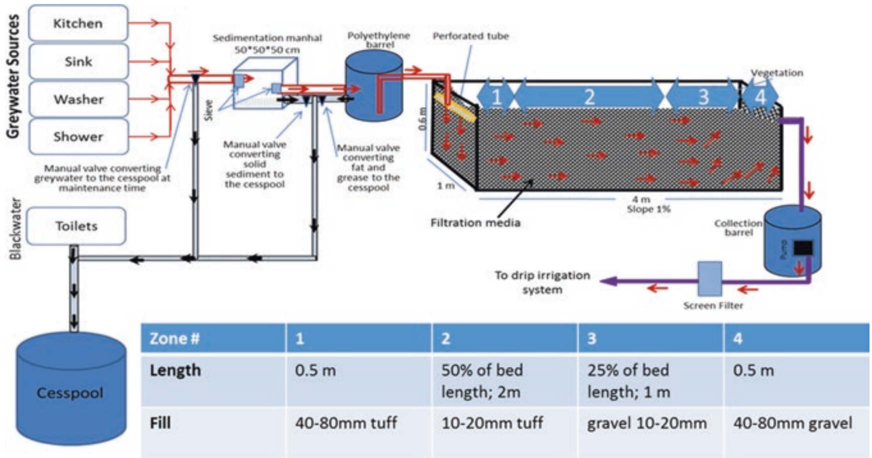
CW treatment systems have been successfully used to treat municipal wastewater with a wide range of inflow concentrations [25]. However, there is limited information about CWs in developing countries particularly those located in arid and semi-arid areas [26–28]. Therefore, we have built and tested two small-scale CW treatment systems (Table 10.4), one with horizontal sub-surface flow (HFCW; Fig. 10.3) and one with vertical sub-surface flow (VFCW; Fig. 10.4) (Table 10.5). For both systems, greywater sources were high strength mixed greywater from the kitchen, washer, shower, and sinks. The water was pre-treated by sedimentation manhal (50*50*50 cm) placed underground, where the solid materials settled. Two plastic bags sieves were installed at the manhole inlet and the outlet, used to screen the greywater. A manual valve was installed in the bottom of the manhal and used to convert the settled solid sediment to the cesspool. The valve was also used to convert raw greywater to a cesspool during the maintenance, emergency cases, and if the family needs to leave their home for a while.

Fat and grease separation phase were removed from filtered graywater by a 100 L polyethylene barrel. The fat and the grease floats on the water surface and then reconverted to the cesspool, while the lower part of the water was siphon by gravity to the HFCW bed. This barrel was also meant to regulate the greywater's

Table 10.4 Design parameters of the Jordanian Horizontal Flow Constructed Wetland

Design steps[a]		Notes
Design parameters	Porosity = 0.35 Hydraulic conductivity = 500 m^3/m^2/day Mean winter water temp = 8 °C Depth = 0.6 m Bed slope = 1%	According to USEPA [32]. Temperature from Al-Samra meteorological station
Design assumption	Expected water to be treated = 0.25 m^2/day Influent BOD_5 = 500 mg/L Intended effluent BOD_5 = 200 mg/L	
Determine the bed surface area	1. Determine the temperature- dependent rate constant (KT). $KT = K20\ (1.1)^{T\text{-}20}$ $KT = 0.86*(1.1)^{(8-20)} = 0.27$	KT: the temperature – dependent rate constant K20: constant at 20 °C = 0.86
	2. Determine the bed surface area $As = (Q(InC_o\text{-}InC_e))/KTdn)$ As = (0.25(5.01–5.3))/(0.27*0.6*0.35) As = 3.89 m^2	As: surface area C_o: influent BOD_5 C_e: effluent BOD_5 Q: expected amount of water to be treated n: porosity d: depth (m)
Determine the bed length and width	For main bed: L = 4 m, W = 1 m. L*W = 4 m^2	L: Length W: Width
Determine detention time	T = LWdn/Q T = (4*1*0.6*0.35)/0.25 = 3.4 days	T: Detention time

[a] *Upon the guidance for design and construction of a sub-surface flow constructed wetland* [32]



Zone #	1	2	3	4
Length	0.5 m	50% of bed length; 2m	25% of bed length; 1 m	0.5 m
Fill	40-80mm tuff	10-20mm tuff	gravel 10-20mm	40-80mm gravel

Fig. 10.3 The construction design of the Horizontal Flow Constructed Wetland (HFCW) in Jordan

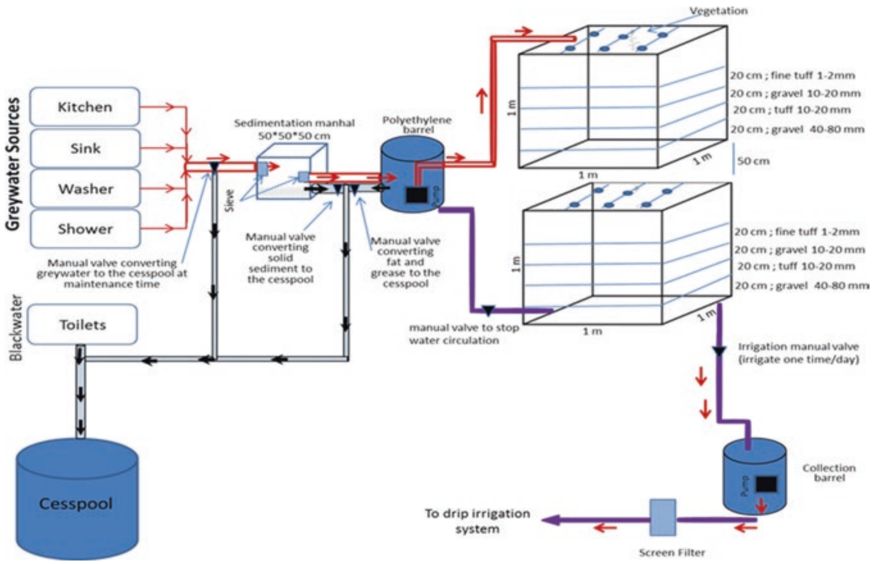


Fig. 10.4 Design of the Vertical Flow Constructed Wetland Treatment System (VFCW) in Jordan

inflow, and to equalize the quality and temperature of the greywater, but in reality, influent flow rate was pulsated with insufficient overlapping to create a continuous flow during the day, and almost zero (i.e., no flow) at night. Therefore, water meter does not work properly and our greywater system operated under uncontrolled intermittent flow conditions.

The CW basin was built of cement bricks and lined by polystyrene sheet to prevent any leaching and groundwater contamination. The dimentions were 4 m × 1 m

Table 10.5 Design parameters of the Jordanian VFCW

Design steps		Notes
Design parameters	The first-order areal rate constant (K). The K value is estimated for low quality greywater as 0.16 m/d.	Upon Kadlec and Knight [33].
Design assumption	Expected amount of water that will be treated = 0.25 m^2/day Influent BOD_5 = 500 mg/L Intended effluent BOD_5 = 200 mg/L Calculated reduction in BOD_5 concentration = 70%	
Determine the required area	(a) Determine the required area (A) $A = \frac{Q}{K} Ln\left(\frac{BOD_{5i} - BOD_{5b}}{BOD_{5e} - BOD_{5b}}\right)$	A: the required VFCW area (m^2), Q: the water flow rate (m^3d^{-1}), BOD_{5e}: the BOD_5 concentration in the treated greywater. BOD_{5i}: the BOD_5 concentration in the raw greywater. BOD_{5b}: the background concentration K: the first-order areal rate constant.
	A = 1.7 m^2	

× 0.6 m (L × W × D) with a 1% slope. The bed was filled with volcanic tuff and gravel, locted in a planted with Pampas grass (planting density one plant per square meter). Water flows horizontally and subsurface inside the bed. Volcanic tuff and gravel were selected as both have good history in water treatment and are available in Jordan environment with affordable price [29–31]. Both volcanic tuff and gravel media have to be washed before using by hydrochloric acid solution (1 M) or with a special cleaning solution.

A collection barrel was installed near the front end of the HFCW. An automatic submersible pump is fixed in the lower collection barrel. An overflow pipe is set up from the submersible pump in the collection barrel to the screen filter. The water was used for irrigation of olive orchard by drip irrigation according to the Jordanian standards for greywater reuse "Reclaimed greywater in rural areas JS1767:2008".

10.3.1 Jordanian CWs Effluent Quality

Each VFCW and HFCW served a single home by treating their greywater and recycling it for home garden supplementary irrigation (i.e., olive and fruit trees). The generated treated greywater from both VFCW and HFCW were compatible with the Jordanian standard for restricted irrigation. The results of the concentration, mass

Table 10.6 The Jordanian greywater standards (JS1767:2008)

Parameter	Irrigation: Trees and fodder irrigation "restricted irrigation"	Landscape and vegetables to be eaten cooked	vegetables to be eaten un cooked	Toilet flushing
BOD_5 (mg/L)	300	60	60	≤10
COD (mg/L)	500	120	120	≤20
TSS (mg/L)	150	100	50	≤10
pH	6–9	6–9	6–9	6–9
NO_3 (mg/L)	50	70	70	70
TN (mg/L)	70	50	50	50
Turbidity	25	Not available	Not available	≤5
E. coli (number/100 ml)	Not specified	10	10	<10
Egg nematodes (number/1 L)	≤1	≤1	≤1	≤1

flow, and removal efficiencies of BOD_5, COD, and TSS show that VFCW and HFCW significantly reduced BOD_5, COD, and TSS concentrations in their effluents. However, the VFCW were more efficient than the HFCW in removing BOD_5, COD, and TSS. The BOD_5, COD, and TSS demonstrated a removal efficiency of 84%, 89%, and 88%, respectively, when using the HFCW, and 90%, 90%, and 92%, respectively, when using the VFCW. Moreover, a noteworthy improvement in the quality of the systems effluents was observed for BOD_5, COD, and TSS, as their average concentration fell within the Jordanian standard maximum allowable concentration (Table 10.6).

The concentration and mass flow for the studied chemical parameters increased after passing through the HFCW. These increases were significant for pH, HCO_3^-, Mg_2^+, Na^+, Cl^-, K^+, $SO4_2^-$, and SAR. However, they were not significant for Ca_2^+. On the other hand, there were no significant differences between concentration and mass flow of these chemical parameters after passing through the VFCW.

The results indicated that the quantity of treated greywater was limited (about 36 l/p/d). however, the typical volume of greywater varies from 90 to 120 l/p/d. The reuse of that limited quantity of water for supplementary irrigation has many direct positive impacts including enhancement of the productivity of olive trees (fruit and oil). Moreover, the households saved 33% and 35% of the average fresh water consumption and monthly water bill, respectively.

10.4 Palestine

According the bureau of statistics in Palestine, only about 60% of the population are connected to sewerage [34]. The percentage of treated wastewater does not exceed half of the collected. In many cases, the topography and financial constraints do not assist in the construction of centralized wastewater treatment facilities, therefore, localized low cost systems may be a feasible and affordable solution given that adequate monitoring of quality is ensured. Al-Sa'ed and Mubarak [35], concluded that septic tank-subsurface wetland system offers a higher level of sustainability to rural communities. The lessons learned from existing pilots and full-scale wetlands in Palestine include the followings:

- Subsurface horizontal flow is the preferred option for wetland setup since vertical flow systems faced excessive mosquito and odor problems that rendered then as socially unacceptable.
- The high organic load in domestic wastewater due to the low per capita water consumption requires higher retention time in the wetlands and therefore larger surface area to achieve acceptable treatment level.
- Vegetation in the wetlands should be kept in the range of 0.5–1.0 m high, which means there is a need to cut (trim) the vegetation 3–4 times each year. Less frequent trimming will increase the water loss through transpiration and more frequency trimming will affect the normal growth of plants and affect the ability of roots to uptake and remove nutrients.
- Wetlands should be designed carefully to avoid dead area and water stagnation points (usually corners of rectangular basins) and short-circuiting of wastewater due to uneven distribution of vegetation across the wetland.

10.5 Conclusions

The experiences from CW systems in the countries of Israel, Jordan and Palestine can be summarized as follows:

(a) Constructed wetlands media (gravel or tuff) and the presence and type of plants are important at early stages of CW but upon maturation they make little to no difference, suggesting that plant and the transpiration water loss associated with them can probably be avoided.
(b) At least under the local conditions, constructed wetlands gave good removal of bacteria but less than satisfactoty of nutrients. This might be acceptable if the effluent is used for irrigaton and nutrients in the water are used as fertelizer replacment, but long-term tests of the effects on soil and crop are needed.
(c) In the case of Jordan, water quality analyses suggseted that both, the HFCW and the VFCW types were effective in treating high strength greywater and generating effluent suitable for limmited irrigation.
(d) Constructed wetlands, if built and implimented properly could help aliviate water stress in arid and semi-arid climatic conditions, especialy in rural areas where centralised systems are not practical.

Acknowledgments The work described here was partially funded by the USAID Middle East Regional Cooperation fund M32-020.

References

1. Worldbank, available at https://data.worldbank.org/indicator/AG.LND.PRCP.MM?view=map. Accessed 20 Jan 2021
2. Bahadir M, Aydin ME, Aydin S, Beduk F, Batarseh M (2016) Wastewater reuse in Middle East countries – prospects and challenges. Fresenius Environ Bull 25(5):1284–1304
3. WWAP (2017) The United Nations World Water Development Report 2017: wastewater: the untapped resource. Hg. v. WWDR. United Nations Educational, Scientific and Cultural Organization. Paris, France
4. Azaizeh H, Linden KG, Barstow C, Kalbouneh S, Tellawi A, Albalawneh A, Gerchman Y (2013) Constructed wetlands combined with UV disinfection systems for removal of enteric pathogens and wastewater contaminants. Water Sci Technol 67(3):651–657
5. Saidan MN, Al-Addous M, Al-Weshah RA, Obada I, Alkasrawi M, Barbana N (2020) Wastewater reclamation in major Jordanian industries: a viable component of a circular economy. Water 2020(12):1276. https://doi.org/10.3390/w12051276
6. Volodymyr T, Sirajuddin A, Viktor P (2007) Modeling constructed wetland system performance. Ecol Model 205(3–4):355–364
7. WWAP (2018) The United Nations World Water Development Report 2018: nature-based solutions for water. Hg. v. WWDR. United Nations Educational, Scientific and Cultural Organization. Paris, France
8. Fuchs VJ, Mihelcic JR, Gierke JS (2011) Life cycle assessment of vertical and horizontal flow constructed wetlands for wastewater treatment considering nitrogen and carbon greenhouse gas emissions. Water Res 45(5):2073–2081
9. Wu S, Carvalho PN, Müller JA, Manoj VR, Dong R (2016) Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators. Sci Total Environ 541:8–22
10. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East review. Water 2020(12):1665. https://doi.org/10.3390/w12061665
11. Abou-Kandil A, Shiblia A, Azaizeh H, Wolff D, Wick A, Jadoun J (2021) Fate and removal of bacteria and antibiotic resistance genes in horizontal subsurface constructed wetlands: effect of mixed vegetation and substrate type. Sci Total Environ 759:144193
12. Gerchman Y, Sayed F, Abou-kandi A, Abu Tayeh H, Azaizeh H (2018) Using sugarcane as constructed wetlands plant for better economic viability. Using sugarcane as constructed wetlands plant for better economic viability. CEBAS-CSIC, Spain
13. Correia AC, Swan KD, Huynh QA (2020) Decentralized wastewater treatment in Southern Israel. Retrieved from https://digitalcommons.wpi.edu/iqp-all/5605
14. Saz Ç, Türe C, Türker OC, Yakar A (2018) Effect of vegetation type on treatment performance and bioelectric production of constructed wetland modules combined with microbial fuel cell (CW-MFC) treating synthetic wastewater. Environ Sci Pollut Res 25:8777–8792. https://doi.org/10.1007/s11356-018-1208-y
15. Zamora S, Sandoval L, Marín-Muñíz JL, Fernández-Lambert G, Hernández-Orduña MG (2019) Impact of ornamental vegetation type and different substrate layers on pollutant removal in constructed wetland Mesocosms treating rural community wastewater. PRO 7:531. https://doi.org/10.3390/pr7080531
16. Zhu H, Zhou Q-W, Yan B-X, Liang Y-X, Yu X-F, Gerchman Y, Cheng W-W (2017) Influence of vegetation type and temperature on the performance of constructed wetlands for nutrient removal. Water Sci Technol 77(3):829–837
17. Tanner CC, Sukias JPS, Headley TR, Yates CR, Stott R (2012) Constructed wetlands and denitrifying bioreactors for on-site and decentralised wastewater treatment. Comparison of five alternative configurations. Ecol Eng 42:112–123
18. Menon R, Jackson CR, Holland MM (2013) The influence of vegetation on microbial enzyme activity and bacterial community structure in freshwater constructed wetland sediments. Wetlands 33:365–378

19. Queluz JGT, Pereira FFS, Sánchez-Román RM (2018) Evapotranspiration and crop coefficient for Typha latifolia in constructed wetlands. Water Qual Res J 53(2):53–60
20. Albalawneh A, Chang T-K, Alshawabkeh H (2017) Greywater treatment by granular filtration system using volcanic tuff and gravel media. Water Sci Technol 75(10):2331–2341
21. DOS (2011) Department of Statistics (DOS). Jordan in Figures 2010; Department of Statistics: Amman, Jordan, Issue 13
22. Whitman E (2019) A land without water: the scramble to stop Jordan from running dry. Nature 573:20–23
23. Dalahmeh SS, Hylander LD, Vinneras B, Pell M, Oborn I, Jonsson H (2011) Potential of organic filter materials for treating greywater to achieve irrigation quality: a review. Water Sci Technol 63:1832–1840
24. Ghaitidak DM, Yadav KD (2013) Characteristics and treatment of greywater—a review. Environ Sci Pollut Res 20:2795–2809
25. Wu H, Zhang J, Ngo HH, Guo W, Hu Z, Liang S, Fan J, Liu H (2015) A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. Bioresour Technol 175:594–601
26. Kivaisi AK (2001) The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. Ecol Eng 16:545–560
27. Albalawneh A, Chang T-K, Chou C-S, Naoum S (2016) Efficiency of a horizontal sub-surface flow constructed wetland treatment system in an arid area. Water 8:51
28. Zhang DQ, Jinadasa KBSN, Gersberg RM, Liu Y, Ng WJ, Tan SK (2014) Application of constructed wetlands for wastewater treatment in developing countries – a review of recent developments (2000–2013).J. Environ Manag 141:116–131
29. Al-Anber M, Al-Anber ZA (2008) Utilization of natural zeolite as ion-exchange and sorbent material in the removal of iron. Desalination 225:70–81
30. NRA (2015) Natural Resources Authority (NRA), http://www.nra.gov.jo/index.php?option=com_content&task=view&id=41&Itemid=66
31. Yousef RI, El-Eswed B, Alshaaer M, Khalili F, Khoury H (2009) The influence of using Jordanian natural zeolite on the adsorption, physical, and mechanical properties of geopolymers products. J Hazard Mater 165:379–387
32. USEPA (1993) Guidance for design and construction of a subsurface flow constructed wetland (August)
33. Kadlec RH, Knight RL (1996) Treatment wetlands. Lewis Publishers, Boca Raton
34. PCBS – Palestinian Central bureau of Statistics (2019) Palestine in Figures. Printed report (in Arabic)
35. Al-Sa'ed R, Mubarak S (2006) Sustainability assessment of onsite sanitation facilities in Ramallah-Albireh district with emphasis on technical, socio-cultural and financial aspects. Manag Environ Qual 17(2):140–156

Chapter 11
Performance of Decentralized Vertical Flow Constructed Wetlands for Reuse in Agricultural Irrigation in Jordan: Enhancing Nitrogen Removal

Ghaida Abdallat and Noama Shareef

Abstract This study shows the performance of two vertical flow constructed wetlands (VFCW) at the Fuhais research facility for decentralized wastewater treatment in Jordan, considering category-A in the Jordanian Standards for reuse in irrigation (JS 893/2006). Recirculating and two-stage VFCW designs were monitored for 3 years. The recirculating VFCW has shown high removal efficiency of COD, TSS, and BOD_5 over the study period, conforming to the JS (Category A). Whereas, the Total Nitrogen (TN) and Nitrate (NO_3^-) removals were limited (55 and 44 mg/L) over the baseline monitoring, conforming to the JS category-B (TN: 70 mg/L and NO_3-N: 45 mg/L). Therefore, the system was modified into attached growth recirculation tank (installing electric conduit pipes as plastic media). TN concentration was effectively reduced to 40 mg/L, conforming to the JS category-A (TN: 45 mg/L), and NO_3^--N concentration to 37 mg/L, conforming to the JS category-B. The two-stage VFCW has shown high removal efficiency of COD, TSS, and BOD_5, conforming to the JS (Category-A). TN and NO_3^--N concentrations were limited (55 and 44 mg/L), conforming to the JS Category-B, due to insufficiency of carbon source to promote denitrification (high BOD_5 removal by the first filter). Thus, the system was modified with raw wastewater step-feeding application to the intermediate pump shaft before the second stage filter. The results of operational modification showed a small significant improvement in TN removal ($p = 0.005$); TN and NO_3^--N concentrations were reduced to 52 and 50 mg/L, respectively, conforming to the JS (Category-B).

Keywords Arid climate · Vertical flow constructed wetland · Recirculating · Nitrogen · Nitrification · Denitrification · Reuse · Jordan

---

G. Abdallat
Postdoctoral Researcher, University of Jordan, Amman, Jordan

N. Shareef (✉)
Water Policy officer at the European Water Association EWA, Bonn, Germany

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_11

11.1 Introduction

In arid and semi-arid countries, recycling treated wastewater in irrigation is a widespread practice. Therefore, robust treatment designs are required to obtain effluent quality that conforms to the legal requirements and guidelines for reuse and health standards. Decentralized wastewater treatment (DWWT) technologies can protect water resources by providing an appropriate treatment for reuse on a local scale [1]. DWWT is implemented to treat and dispose wastewater from rural areas and small settlements instead of constructing or upgrading centralized wastewater treatment facilities.

Constructed wetlands (CWs) are appropriate for DWWT in unsewered settlements and villages due to their technical simplicity, high treatment efficiency, cost effectiveness, and successful application in developed countries [2, 3]. In arid areas, VFCWs present high oxygen transfer capacity, high organic matter removal, high nitrification rate, lower evapotranspiration rates (for unplanted bed) [4]. The water in VFCW systems is treated by a combination of physical treatment processes (sedimentation and filtration), chemical processes (ion exchange, adsorption and chemical oxidation processes), and biological processes (nitrification, denitrification, microbial degradation, predation, natural die-off, and plant uptake) [3, 5–7]. Besides, VFCW systems could be designed with small area in order to reduce the evaporation rates and water losses [4]. On the other hand, VFCWs do not achieve full denitrification, and thus, removal of total nitrogen (TN) is limited typically to 20–30% [8]. The nitrogen removal mechanisms in the VFCWs include ammonification, nitrification, denitrification, plant uptake, and physicochemical routes such as sedimentation, ammonia volatilization, and ion exchange [6, 9–11]. Thus, several studies have been optimized the nitrogen removal process in CWs [9, 12–15].

Jordan, as an arid country, has limited surface and groundwater resources and has unpredictable rainfall in winter season, ranging from around 660 mm in the northwest to less than 130 mm in the east [16]. The kingdom's potable water availability is only 145 m^3/capita/year, which is below "water poverty line" of 1000 m^3/capita/year [17]. However, currently, Jordan has stressful water situation with increasing population growth, wave's refugees, agricultural demands, and climate change. Therefore, Jordan water strategy considers treated wastewater as a water source increasing with increasing consumption of fresh water. Additionally, treated wastewater has been considered as valuable water for irrigation rich with natural fertilizers [18–20].

The Jordanian Standards (JS) 893/2006 guidelines for reuse in irrigation and other purposes of treated wastewater were prepared for centralized wastewater treatment plants. That major cities in most developing countries are served by centralized sanitation systems [21]. Whereas, in developed countries, the adoption of DWWT supports effectively different reuse options [22]. Table 11.1 shows the JS for reuse in irrigation consisting of four categories: A, B, C, and D. Each category shows water quality required for different crops; however, they do not address the level of treatment (primary, secondary, tertiary or advanced).

Table 11.1 The Jordanian standards for treated wastewater reuse in irrigation (893/2006) [23]

Parameter	A (1)	B (2)	C (3)	D (4)
BOD_5 [mg/L]	30	200	300	15
COD [mg/L]	100	500	500	50
DO [mg/L]	>2	–	–	>2
TSS [mg/L]	50	150	150	15
pH (−)	6–9	6–9	6–9	6–9
Turbidity [NTU]	10	–	–	5
NO_3-N [mg/L]	30	45	45	45
TN [mg/L]	45	70	70	70
E. coli [MPN/100 mL]	100	1000	–	<1.1
Intestinal helminth eggs [egg/L]	< or = 1	< or = 1	< or = 1	< 1
Grease, oils and fats [mg/L]	8	8	8	8

1 cooked vegetables, parks, playgrounds and sides of roads within city limits
2 fruit trees, sides of roads outside city limits and landscape
3 field crops industrial crops and Forest trees
4 cut flowers

Nevertheless, DWWT have no explicit standards and are, thus, assumed to follow the regulations for centralized wastewater treatment plants. That, in the JS 893/2006, total nitrogen is limited to 45 mg/L in class A, and 70 mg/L in B, C and D classes, depending on the sensitivity of plants in each group. Therefore, this study focuses on the baseline treatment efficacy of recirculating and two-stage VFCWs and their operational modifications for improved TN removal in Jordan.

11.2 Materials and Methods

11.2.1 Site Description

Fuhais research and demonstration site has established within the SMART project (Sustainable water Management of Available water Resources with innovative Technologies) in 2010. The site is located at the edge of both Fuhais and Mahis cities, nearby Amman, at the campus of the centralized wastewater treatment plant (serving about 25,000 inhabitants) for Fuhais and Mahes cities (Fig. 11.1).

The site accommodates different decentralized wastewater treatment plants (modified septic tanks, sequencing batch reactors, continuous batch reactors, membrane bio-reactor, sludge dewatering reed beds, and two unsaturated VFCWs). The first VFCW is a single-stage recirculating system, and the second is a two-stage VFCW. The research site also hosts three reuse fields, where treated wastewater is applied to crops of lemon trees.

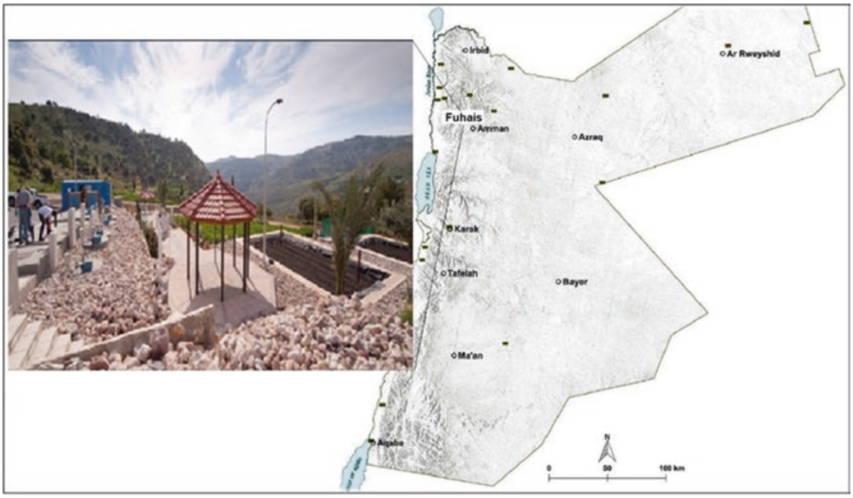


Fig. 11.1 Fuhais research and demonstration facility for decentralized wastewater treatment technologies and reuse in Jordan

A collection tank at the site receives primary screened raw wastewater from the main wastewater. Then, raw wastewater is distributed intermittently into each technology by submersible pumps in the collection tank. The inflow and outflow for each technology are measured using an electromagnetic flowmeter and the discharge is controlled using a SIEMENS-SIMATIC S7–200 PLC. The treated effluent from each technology is collected in a separate irrigation tank. The research facility is equipped with on-site laboratory where water quality analyses are conducted.

11.2.2 Experimental Setup

Two pilot-scale ecotechnologies were designed and constructed. The first system is a recirculating gravel filter, and the second system is a two-stage vertical flow filter. Each system has a septic tank, which provides primary treatment to the wastewater before it is dosed to the filter. The inflow and outflow for each system was measured using an electromagnetic flowmeter connected to a PLC system. In addition, effluent from filters was measured by calibrated tipping buckets (40.6 L/tip) mounted at the irrigation tanks. All inflow and outflow readings (from PLC and tipping buckets) were recorded on a daily basis in the morning. This study consisted of two phases; the first phase was monitoring the systems in order to identify the suitable options for optimizing the TN removal in these systems; then the second phase was monitoring after implementation of an operational modification.

11.2.3 Recirculating VFCW

The recirculating system consists of a septic tank, recirculation tank, unsaturated vertical flow filter and flow splitting-box, as shown in Fig. 11.2. Figure 11.3 shows the system layout. The system was designed to treat 2.16 m^3/d with an average hydraulic load of approximately 108 L/m^2/d. The raw wastewater received primary treatment in a septic tank (4.6 m^3) with an approximate residence time of 2 days. The effluent from the septic tank moves passively through a T section to the recirculation tank (4.6 m^3). The water is pumped from the shaft tank to the filter using a submersible pump. The splitting-box placed at the outlet where the effluent is passively distributed via a V-notch weir. That 25% of the effluent goes to the irrigation tank and the 75% back to the recirculation tank (3:1 recirculation ratio) (Fig. 11.3).

The system had a surface area of 20 m^2 (4 m width, 5 m length) and 1 m depth (Fig. 11.4). The filter is filled with zeotuff gravel (4–8 mm) and had a filter depth of 0.8 m. The water is dosed to the top of the filter via inlet distribution pipelines (perforations every 0.5 m), which are covered by a half-pipe shield tunnel. The distribution pipelines contained risers to enable flushing out of the accumulated solids from

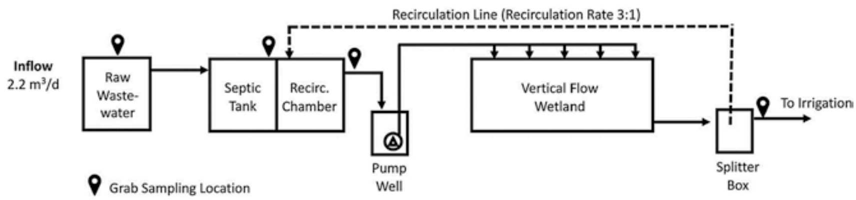


Fig. 11.2 Schematic of the recirculating VFCW [24]

Fig. 11.3 The VFF with the flow splitting-box at Fuhais, Jordan

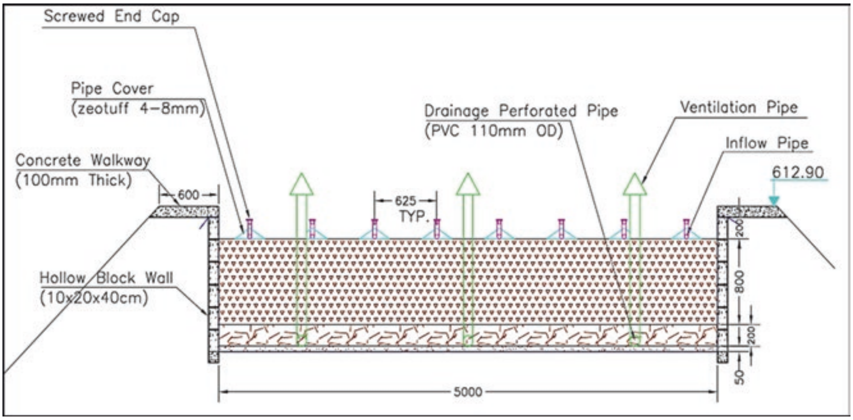


Fig. 11.4 The profile view of the unsaturated VFCW

the pipelines. Lateral vertical pipes are connected with the drainage system (110 mm diameter) in the bottom bed, promoting a passive oxygenation. The bottom of each bed is sealed by a geotextile fabric to prohibit any kind of leakage.

11.2.3.1 Operational Modification

This system was modified to enhance nitrogen removal to fulfill the 45 mg TN/L in the JS (category-A). Al-Zreiqat et al. [25] and Shareef [26] conducted a microcosm experiment at the Fuhais laboratory to investigated the effect of attached-growth media in the recirculation tank on denitrification. The studies showed high level of denitrification (low NO_3-N concentration) using attached-growth media in the recirculation tank.

Thus, six groups of five mesh bags (each bag containing 120 pieces of plastic electrical conduit with 4 cm/piece length) were tied together and installed in the recirculating tank as shown in Fig. 11.5. The total volume occupied by the sacks was estimated to be approximately 150 L. The post modification monitoring period was conducted for (47 weeks). Dry weight of biofilm on the plastic media was measured (4268.16 mg/m^3) after 10 months of installation, as described by Bratbak et al. [27] and Nouvion et al. [28].

11.2.4 Two-Stage VFCW System

The two-stage VFCW consists of a septic tank and two unsaturated filters in series (Fig. 11.6). The system was designed to treat 3.2 m^3/day, with an average hydraulic loading rate of approximately 80 and 56 L/m^2/d for the first and second filters,

Fig. 11.5 Prepared plastic media (Pieces of conduit in mesh bags)

Fig. 11.6 The two-stage treatment wetland, first stage (single-pass) and second stage (planted bed) at the site

respectively. The first unplanted filter (40 m^2) was designed in a passive structure (no pump) treatment processes. The second filter (57 m^2) was planted with *Phragmites Australis*. Figure 11.7 shows the system diagram. The VFCWs were monitored with and without plants to assess the plant effect on the treatment performance and water balance.

The first stage filter consists of 100 cm of 2–4 mm Zeotuff, underlain by a 10 cm transition layer of 4–8 mm Zeotuff. Under that is a 20 cm layer of 10–25 mm Zeotuff (Fig. 11.8). The bottom of the bed has a 2% slope. The drainage layer contains 100 mm perforated drainage pipe. The second stage filter consists of 100 cm of 2–4 mm Zeotuff underlain by a 5 cm transition layer of 4–8 mm Zeotuff. The drainage layer consists of approximately 20 cm of 10–25 mm Zeotuff. The filter has a 1% bottom slope. The drainage layer contains 100 mm perforated drainage pipe. The system also was constructed with a diversion manhole and two tanks in between the

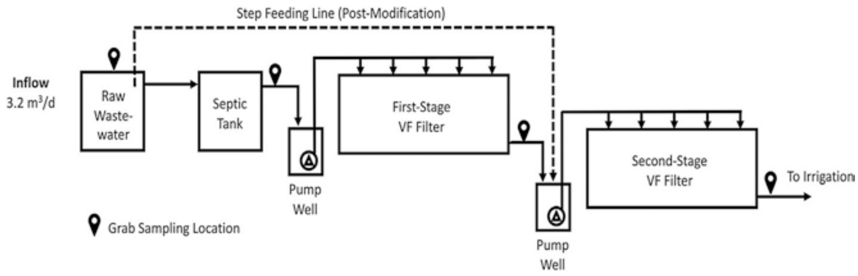


Fig. 11.7 The two-stage VFCW scheme during the study [24]

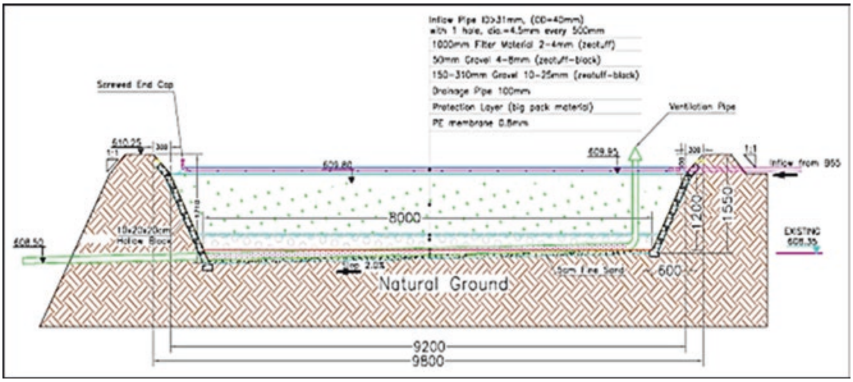


Fig. 11.8 Profile view of the first stage (single-pass) in the two-stage system

first and second filters. These tanks were filled with woodchips for subsequent anaerobic conditions of the first-stage effluent. The second stage filter was primarily meant for further removal of pathogenic organisms. Early experience with the woodchip filter highlighted a critical problem with this approach. Woodchips, or other similar material, are not readily available in Jordan, and no other suitable material could be found. As such, the two tanks were emptied of the spent woodchips and taken out of service. A small pump well was installed in the diversion manhole, which served as the pump well for mixing of raw wastewater and effluent from the first-stage filter.

11.2.4.1 Operational Modification

A step-feeding line was introduced as an operational modification to improve TN removal in the system. Raw wastewater was pumped to the pump well downstream of the first filter, where it mixed with treated effluent from the first stage filter. The mixed water (raw wastewater with first stage effluent) was then intermittently pumped to the second stage filter. An estimate of the carbon required to denitrify the nitrate-nitrogen in the effluent of the first stage wetland to the level of the Class A standard for TN (45 mg/L), based on a carbon requirement of approximately 3 g of organic matter per gram of NO_3-N [3] resulted in a daily amount of raw wastewater of approximately 440 L/d. A pump was used to deliver 330 L of raw wastewater per day (in five intermittent doses) to the pump shaft downstream of the first stage filter.

11.2.5 Sampling and Water Quality Analysis

Water samples were collected weekly (February 2012 to August 2014) from each component of the systems (before and during modification). Field measurements (pH, EC, turbidity, redox potential and water temperature) were measured directly on-site using the WTW ProfiLine-Cond 3110 probe and WTW multi-meter. Turbidity was measured in Nephelometric Turbidity Units (NTU) using a TU-2016 turbidity meter. The samples were analyzed directly in the laboratory of the site, including COD, TN, NH_4-N, NO_3-N, NO_2-N and PO_4^{3-}-P using HACH LANGE test kits according to Standard Methods Standard Methods for Examination of Water and Wastewater [29]. $CBOD_5$ was measured using OxiTop® manometric OC 100, following the German standard DIN 38409 H52. TSS was analyzed using the gravimetric method according to [29]. *E. coli* was measured in MPN/100 L using the IDEXXTM Colilert-18 Quanti-tray method, according to the manufacturer's specifications.

11.2.6 Statistical Methods

Statistical analyses were performed using SigmaPlot software, version 12.0. The analysis of variance, using one-way ANOVA (statistical significance, $p < 0.05$), was applied between calculated yearly means of pH, EC, DO, turbidity, TSS, TN, NH_4^+-N, NO_3^--N, TOC, and BOD_5. And calculated geometric mean for *E. coli* for the first and second phase in order to investigate the effects of modification in each system.

11.3 Results and Discussion

The treatment performance of the systems was evaluated by the conformity of effluents to the national JS (class A) for reuse in irrigation. The systems` treatment efficiency is presented in two phases: first phase of monitoring system in a steady state

(February 2012 to September 2013) and second phase of monitoring of modified system (attached growth biofilm in a recirculation tank, and raw wastewater step-feeding in the two-stage vertical flow treatment wetland system (October 2013 to August 2014).

11.3.1 Recirculating VFCW

Table 11.2 sumerizes the results of mean pollutant concentrations and standard deviations (SD) for the basline and post-modification phases. The mean values of the previous parameters were statistically similar ($p < 0.05$) during phases 1 and 2. The pH values ranged from 7.1 to 7.6, which is conformed to the JS (pH values of 6–9). There was no significant change in pH values during the treatment process compared with raw wastewater pH, indicating a normal biological nitrification in the system.

The effluent EC was gradually reduced during the treatment process, which can be explained by the settlement of suspended particles and elements [30]. The VF effluent had a mean EC of 1546 μS/cm and 1365 μS/cm during the first and second phase, respectively. During the second phase, higher EC reduction was observed due to higher NO_3^--N removal and it was compatible with influent EC values. On the other hand, no big changes were observed in the inflow and outflow data. However, lower outflow rates (up to 0.5 m^3/d) were observed during summer months due to evaporation from the splitting box (open to the atmosphere) [24]. The EC results conform to the JS (0.7–3000 μS/cm) over the study period.

The effluent DO concentration was 6.2 mg/L. The raw wastewater had a DO concentration of 0.6 mg/L. The effluent was highly oxygenated and fulfilled the JS (DO greater than 2 mg/L). This result was promoted by gas diffusion from the atmosphere between intermittent hydraulic loads as documented by many authors [31, 32]. In phase 2, redox measurements were dramatically increase of +55 and + 143.1 mV in the recirculation tank and VFCW effluent, respectively.

TSS and turbidity were typically high in the raw wastewater over the study period. TSS was reduced from 466 to 10 mg/L during phase 1 and was reduced from 311 to 11 mg/L during phase 2. TSS and turbidity are removed by physical processes such as sedimentation and filtration [3, 33]. Effluent TSS concentrations were compatible with the Jordanian Standards (less than 50 mg/L) (Fig. 11.9a). Recirculating VFCW removed TSS, on average mean removal efficiencies of 97.7% and 96.8%, with mean mass removal rates of 53.5 g/m^2/day and 31.6 g/m^2/day in phase 1 and 2, respectively. Comparing first and second phase, effluent TSS concentrations were statically similar ($p < 0.05$).

Turbidity was reduced from 417 to 12 NTU during phase 1. During phase 2, turbidity values reduced from 435 to 22 NTU, hereby, effluent turbidity did not conform to the JS (less than 10 NTU) (Fig. 11.9b). In the recirculation tank, turbidity values were constant during suspended and attached growth. Therefore, increasing turbidity due to attached growth sloughing is negligible. Turbidity was increased

Table 11.2 Recirculating VFCW water quality data (mean ± SD) of each component during the baseline monitoring and post-modification phases

	Parameters	Raw wastewater	Septic tank out	Recirculation tank out	Recirculating VF effluent	Number of samples
Baseline Phase	pH	7.4 ± 0.3	7.1 ± 0.2	7.2 ± 0.2	7.3 ± 0.2	41
	Field Water Temperature (°C)	21 ± 5	21 ± 5	21 ± 6	21 ± 6	41
	EC (μS/cm)	1831 ± 225	1918 ± 205	1661 ± 210	1576 ± 268	41
	DO (mg/L)	0.7 ± 0.7	1.0 ± 0.5	2.0 ± 1.1	5.8 ± 1.2	41
	Redox Potential (mV)	−269 ± 130	−305 ± 57	−68 ± 119	+9 ± 101	41
	TSS (mg/L)	560 ± 436	198 ± 91	42 ± 43	13 ± 8	40
	Turbidity (NTU)	455 ± 221	709 ± 114	61 ± 53	15 ± 11	40
	COD (mg/L)	1233 ± 632	533 ± 121	147 ± 47	62 ± 61	41
	$CBOD_5$ (mg/L)	418 ± 123	204 ± 89	54 ± 35	13 ± 12	41
	TN (mg/L)	112 ± 41	105 ± 41	59 ± 18	58 ± 20	40
	NH_4-N (mg/L)	63 ± 21	75 ± 21	32 ± 17	3.0 ± 4.5	39
	NO_3-N (mg/L)	0.4 ± 0.5	0.4 ± 0.1	12 ± 11	50 ± 20	40
	NO_2-N (mg/L)	0.05 ± 0.07	0.03 ± 0.01	4.8 ± 5.4	1.2 ± 1.1	41
	$\log_{10}$ *E. coli* (MPN/100 mL)	7.0 ± 0.3	6.5 ± 0.3	5.7 ± 0.6	4.9 ± 0.5	35
Post-modification phase	pH	7.6 ± 0.3	7.2 ± 0.3	7.4 ± 0.2	7.4 ± 0.2	45
	Field water temperature (°C)	20 ± 4	20 ± 5	20 ± 5	20 ± 5	45
	EC (μS/cm)	1627 ± 189	1745 ± 184	1546 ± 488	1368 ± 136	44
	DO (mg/L)	0.6 ± 0.5	0.9 ± 0.5	2.6 ± 0.9	6.2 ± 0.9	45
	Redox potential (mV)	−235 ± 61	−277 ± 46	+55 ± 81	+143 ± 50	42
	TSS (mg/L)	314 ± 94	158 ± 42	31 ± 17	11 ± 6	42
	Turbidity (NTU)	443 ± 241	198 ± 89	50 ± 24	23 ± 11	42
	COD (mg/L)	773 ± 228	513 ± 126	185 ± 69	48 ± 21	43
	$CBOD_5$ (mg/L)	340 ± 108	211 ± 52	60 ± 29	14 ± 9	44
	TN (mg/L)	90 ± 45	90 ± 20	44 ± 10	40 ± 9	45
	NH_4-N (mg/L)	53 ± 16	65 ± 14	24 ± 8	0.8 ± 2.1	45
	NO_3-N (mg/L)	1.0 ± 1.2	0.7 ± 0.7	8.7 ± 6.4	36.7 ± 10.7	44
	NO_2-N (mg/L)	0.06 ± 0.12	0.02 ± 0.01	1.9 ± 2.1	0.4 ± 0.4	45
	$\log_{10}$ *E. coli* (MPN/100 mL)	7.1 ± 0.2	6.7 ± 0.2	6.2 ± 0.5	5.1 ± 0.7	41

substantially in the VFCW bed in phase 2 as a result of low filtration and extracted suspended particles by bed matrix or low adsorption process over time. Comparing first and second phase, effluent turbidity was statistically different at $p < 0.05$.

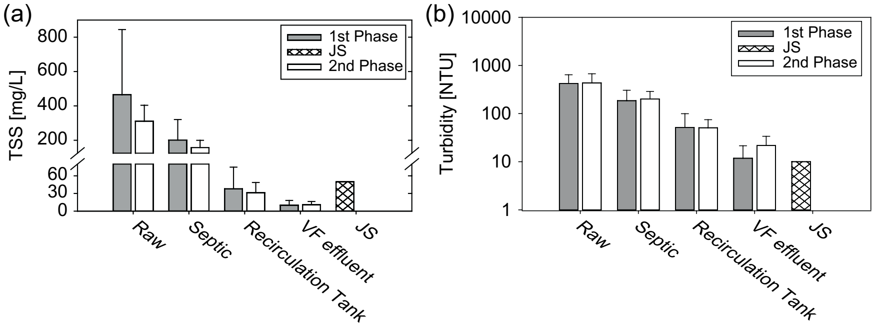


Fig. 11.9 Influent and effluent TSS and Turbidity mean concentrations and SD (error bars) of each component in the system with the JS (class A); (**a**) TSS concentrations over the study period, (**b**) turbidity concentrations over the study period

The mean values of water quality with standard deviations for the post-modification monitoring phase (attached-growth media in the septic tank), i.e., for pH, EC, DO, redox potential, turbidity, and TSS were statistically similar ($p < 0.05$) during the baseline and post-modification phases.

The wastewater is considered as high-strength, even after primary treatment in a septic tank with COD concentrations frequently over 500 mg/L, BOD_5 concentrations often over 200 mg/L, and TN concentrations often over 100 mg/L. The removal of COD and BOD_5 was high and steady throughout the monitoring period, with effluent concentrations of 62 mg/L and 13 mg/L, respectively. COD and BOD_5 removal remained steady in the post-modification period, with average effluent concentrations of 48 mg/L and 14 mg/L, respectively, and conformed to Class A (COD: less than 100 mg/L and BOD_5: less than 50 mg/L) in the JS. In addition, high COD removal rates were observed; on average removal efficiencies were 95.4% and 94.7%, during phase 1 and 2, respectively. No significant difference in COD and BOD_5 concentrations was observed during the baseline and post-modification phases ($p < 0.05$).

Recirculating VFCW system combines simultaneous nitrification and denitrification processes [9, 12]. However, TN removal in the post-modification phase was enhanced, with average effluent concentrations of 40 mg/L in comparison with 58 mg/L baseline phase, meeting the Class A requirement of 45 mg/L (Fig. 11.10a). In phase 2, the higher biomass increased the TN removal rate than suspended growth, similar findings were reported by Al-Zreiqat [25] and Shareef [26]. Effluent TN concentration conformed to the JS (A: 45 mg/L). However, the TN effluents were statistically different ($p < 0.05$) over the study period.

Even if NH_4-N is not a regulated pollutant for JS for reuse, the recirculating system produced well nitrified effluents. NH_4-N effluent concentrations were slightly lower in the post-modification phase of 0.8 ± 2.1 mg/L than effluents NH_4-N concentrations over the baseline phase of 3.0 ± 4.5 mg/L. No significant difference in

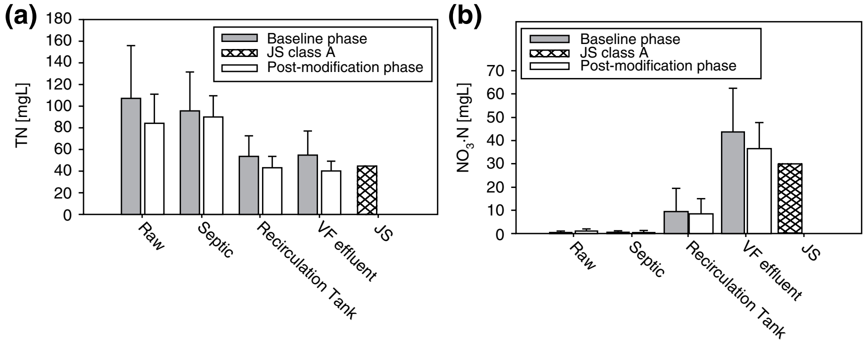


Fig. 11.10 TN and NO_3^--N mean concentrations and SD (error bars) of each component in the recirculating VFCW system; (**a**) TN mean concentrations, and (**b**) NO_3^--N mean concentrations with the JS (class A) over the study period

NH_4-N concentrations was observed during monitoring the system ($p > 0.05$). Well nitrified effluent can be shown by low NO_2^--N mean concentrations in the filter effluent. NO_2-N nitrogen is also not included in the JS, but NO_2-N concentrations in the recirculation tank (1.9 ± 2.1 mg/L compared to 4.8 ± 5.4 mg/L) and final effluent (0.4 ± 0.4 mg/L compared to 1.2 ± 1.1 mg/L) were reduced after the installation of attached growth media in the recirculation tank. The reduction in NO_2^--N values in phase 2 can be explained by enhanced denitrification capacity and low NH_4^+-N input. However, no significant difference in NH_4^+-N concentrations was observed between first and second phase ($p > 0.05$).

NO_3^--N level higher than the recommended levels in the JS (class A: 30 mg/L and B: 45 mg/L) (Fig. 11.10b). During phase 2, NO_3^--N concentrations decreased to 37 mg/L in the VF effluent as a result of stirring denitrification with attached biofilm. Thus, effluent NO_3^--N concentration conformed to the JS class B. Changing from suspended to attached growth increased the abundance and activity of microorganisms. Kadlec and Wallace [3] reported that density and activity of microbes are influenced by changing one or more factor in treatment setup. Post-modification effluent NO_3-N concentrations were slightly lower (37 ± 11 mg/L) than effluent NO_3-N concentrations (50 ± 20 mg/L) during the baseline phase, which conforms with the trends observed for TN (Fig. 11.10b). Therefore, NO_3^--N concentrations were statistically compared; results indicate that the effluents were significantly different ($p < 0.05$).

Over the study period, the system achieved approximately 2.1 $\log_{10}$ *E. coli* reduction; 1.1 $\log_{10}$ was achieved throughout septic and recirculation tank and 1 $\log_{10}$ was achieved by the filter itself [7]. Effluent *E. coli* concentrations were not compatible with the JS (class A), but did conform to class C in the JS. Effluent *E. coli* concentrations were statistically similar ($p > 0.05$) over the study period.

11.3.2 Two-Stage VFCW

Inflow was stable and averaged 3.4 m^3/d during the baseline of monitoring and 3.2 m^3/d in the post-modification phase. Whereas, higher water losses were reported in the second filter (planted bed) as a result of high evapotranspiration of 1.2 m^3/d. However, outflow data for the second VF is not available due to a faulty tipping counter. Unfortunately, during the post-modification phase the outflow of the second VF filter was much higher than proposed, due to incorrect installation of the timer running the step-feeding pump. The step-feed volume was on the order of 2–10 m^3/d based on the tipping counter data from the second VF filter. Further details reported by Nivala et al. [24]. The two-stage VFCW results (mean pollutant concentrations and standard deviations) for the basline and post-modification phases are summarized in Table 11.3.

The mean pH values ranged from 7.3 to 7.7, which conform to the JS (6–9). In the first stage, the pH decreased due to OM decomposition and nitrification. However, there was no significant change in pH values during the treatment process. The effluent EC was gradually reduced until the first stage VF (unplanted bed), on average 1682 μS/cm in the first phase and 1527 μS/cm in the second phase due to high settlement of suspended particles and elements [30, 34]. Subsequently, the effluent EC increased through filtration in the second stage (planted bed), on average 1969 μS/cm and 1854 μS/cm in the first and second phase, respectively. The EC increment can be explained by increasing salts concentrations due to water loss via evapotranspiration. Furthermore, plant root exudates stimulate solubility of some salts and elements from the VF bed matrix. High EC variation (SD) was observed over the study course related to the varying received water quantity and quality. The EC results conformed to the JS (0.7–3000 μS/cm) over the study period.

Whereas, during step-feeding application, mean DO content in the second stage was diminished from 7 into 4.8 mg/L in the second filter due to mixing with unoxygenated wastewater. High DO effluent is a result of intermittent load and plants oxygenation. Vymazal et al. [5] reported that *Phragmites australis* species has a transfer potential of 2 gO_2/m^2/d to the root zone. Effluent DO content conformed to the JS (higher than 2 mg/L) over the study period. During phase 2, the redox measurements increased to +148 and + 177 mV in the first and second stage, respectively. In step-feeding (mixing) tank, low redox level was measured, on average of +28 mV, providing anoxic condition for denitrification.

On the other hand, high variation in TSS influent was observed during phase 1 due to the changes in the quantity of water usage. TSS concentrations were reduced to 3.8 mg/L in the first stage and reduced to 1.6 mg/L in the second stage, indicating high TSS removal via sedimentation and filtrating capacity. During phase 2, the mean TSS effluent of second stage was measured at 3.6 mg/L due to additional TSS from raw step-feeding. Effluent TSS concentrations were highly compatible with the JS (class A: less than 50 mg/L). The mean values of pH, EC, DO, redox potential, turbidity, and TSS were statistically significant ($p > 0.05$) during the baseline and post-modification phases.

Table 11.3 Two-stage VFCW water quality data (mean ± SD) of each component over the study period

	Baseline (09.10.2012–25.09.2013; 50 weeks)	Raw wastewater	Septic tank out	First stage out	Intermediate pump shaft	Second stage out	Number of samples
Baseline phase	pH	7.5 ± 0.3	7.5 ± 0.1	7.4 ± 0.2	–	7.7 ± 0.2	47
	Field water temp. (°C)	21 ± 5	21 ± 4	22 ± 5	–	23 ± 5	47
	EC (µS/cm)	1826 ± 227	1911 ± 185	1689 ± 172	–	1994 ± 376	47
	DO (mg/L)	0.7 ± 0.7	1.8 ± 1.3	5.3 ± 0.6	–	6.9 ± 1.0	47
	Redox potential (mV)	−260 ± 141	−279 ± 79	+73 ± 130	–	+131 ± 114	47
	TSS (mg/L)	534 ± 413	130 ± 81	4.2 ± 2.8	–	1.5 ± 1.6	46
	Turbidity (NTU)	443 ± 226	134 ± 77	6.5 ± 6.1	–	1.6 ± 1.9	46
	COD (mg/L)	1171 ± 623	454 ± 146	34 ± 9	–	23 ± 10	47
	$CBOD_5$ (mg/L)	405 ± 126	173 ± 64	10 ± 6	–	6 ± 5	45
	TSS (mg/L)	534 ± 413	130 ± 81	4.2 ± 2.8	–	1.5 ± 1.6	46
	Turbidity (NTU)	443 ± 226	134 ± 77	6.5 ± 6.1	–	1.6 ± 1.9	46
	TN (mg/L)	115 ± 52	104 ± 28	75 ± 25	–	77 ± 26	41
	NH_4-N (mg/L)	64 ± 21	76 ± 15	0.5 ± 0.4	–	0.03 ± 0.02	46
	NO_3-N (mg/L)	0.4 ± 0.5	0.4 ± 0.1	68 ± 20	–	82 ± 31	44
	NO_2-N (mg/L)	0.05 ± 0.07	0.03 ± 0.01	0.4 ± 0.5	–	0.04 ± 0.04	39
	$\log_{10}$ *E. coli* (MPN/100 mL)	7.0 ± 0.3	6.6 ± 0.3	4.7 ± 0.5	–	2.5 ± 0.5	39

(continued)

Table 11.3 (continued)

	Baseline (09.10.2012–25.09.2013; 50 weeks)	Raw wastewater	Septic tank out	First stage out	Intermediate pump shaft	Second stage out	Number of samples
Post-modification phase	pH	7.6 ± 0.3	7.6 ± 0.3	7.5 ± 0.3	7.7 ± 0.2	7.3 ± 0.3	44 (35[a])
	Field water temp. (°C)	20 ± 4	20 ± 5	21 ± 5	20 ± 5	20 ± 4	45 (35[a])
	EC (µS/cm)	1618 ± 180	1743 ± 182	1527 ± 143	1257 ± 148	1854 ± 166	44 (35[a])
	DO (mg/L)	0.6 ± 0.5	1.5 ± 1.0	6.0 ± 0.8	1.5 ± 1.2	4.8 ± 0.8	44 (35[a])
	Redox potential (mV)	−232 ± 59	−236 ± 49	+148 ± 85	+28 ± 181	+177 ± 119	42 (33[a])
	TSS (mg/L)	311 ± 93	107 ± 56	4 ± 2	85 ± 57	4 ± 2	41 (33[a])
	Turbidity (NTU)	435 ± 237	230 ± 117	11 ± 11	130 ± 85	12 ± 11	40 (35[a])
	COD (mg/L)	774 ± 226	446 ± 117	30 ± 13	279 ± 135	35 ± 18	42 (32[a])
	$CBOD_5$ (mg/L)	340 ± 108	186 ± 52	9 ± 7	54 ± 23	10 ± 7	43 (34[a])
	TN (mg/L)	84 ± 27	84 ± 17	70 ± 15	64 ± 16	52 ± 15	37 (34[a])
	NH_4-N (mg/L)	52 ± 14	66 ± 17	0.7 ± 1.7	24 ± 28	0.2 ± 0.2	45 (34[a])
	NO_3-N (mg/L)	1.0 ± 1.2	1.2 ± 1.4	54 ± 13	36 ± 15	50 ± 22	43 (34[a])
	NO_2-N (mg/L)	0.06 ± 0.12	0.05 ± 0.10	0.3 ± 0.8	1.7 ± 1.2	0.3 ± 0.4	44 (34[a])
	$\log_{10}$*E. Coli* (MPN/100 mL)	7.1 ± 0.2	6.6 ± 0.2	4.7 ± 0.8	5.9 ± 1.5	4.7 ± 1.0	40 (39[a])

[a] Number of samples for intermediate pump shaft

The majority of pollutant (TSS, COD, BOD_5 and turbidity) was removed through the first VF filter. Therefore, the second-stage filter provided further polishing step, with mean effluent concentrations of COD, BOD_5, TSS, and NH_4-N of 23 mg/L, 6 mg/L, 1.5 mg/L, and 0.03 mg/L, respectively, in compliance with JS category A. During the Post-modification phase, mean effluent concentrations for COD, $CBOD_5$ and TSS were 35 mg/L, 10 mg/L and 4 mg/L in the final effluent, respectively, conformed to category A in the JS.

During phase 2, BOD_5 was highly removed even with step-feeding application, on average removal efficiencies of 98.1 and 93.9% in the first and second stage, respectively. Whereas, it was slightly reduced during step feeding 97.1 and 90.8% in the first and second stage, respectively.

On the other hand, turbidity removal decreased from 1.6 NTU (in the baseline phase) to 12 NTU in the post modification phase (12 NTU) as a result of raw wastewater step-feeding modification. It is also correlated with hydraulic overloading, which reduce the hydraulic residence time and filtering time. Comparing the first and second phase effluents, turbidity of VFCW effluents was statistically different at $p < 0.01$.

This system did not remove TN in the baseline monitoring phase, with an average final effluent concentration of 77 mg/L, due to lack of denitrification (low carbon source and anoxic conditions). Many studies reported the improvement of TN removal in VF and HF CW by adopting a step-feeding strategy [9, 14, 15]. TN removal in the post-modification phase enhanced, with average effluent concentrations of 40 mg/L in comparison with 58 mg/L baseline phase, meeting the Class B requirement of 45 mg/L (Fig. 11.11a).

Mean NO_3^--N effluent concentrations were increased in the first and second stage, during the baseline phase, with average effluent concentrations of 82 and 62 mg/L, respectively. NO_3^--N level was higher than the recommended levels in the JS Class A (30 mg/L) (Fig. 11.11b). During the post-modification phase, mean

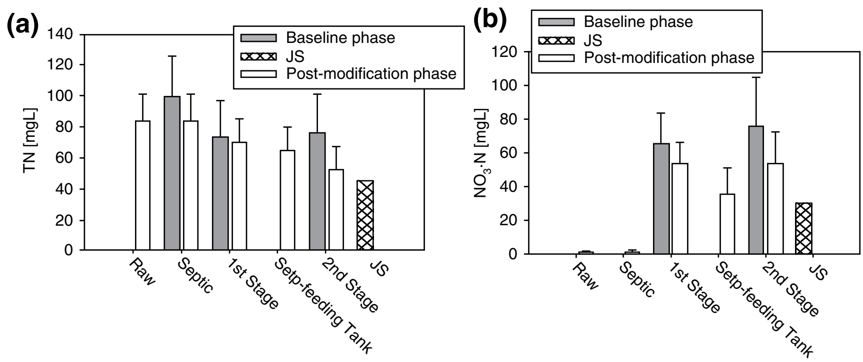


Fig. 11.11 TN and NO_3^--N mean concentrations and SD (error bars) of each component in the two-stage VFCW with the JS (class A) over the study period; (**a**) TN mean concentrations, and (**b**) NO_3^--N mean concentrations with the JS (class A) over the study period

effluent NO_3^--N concentration was decreased in the second stage to 50.2 mg/L as a result of stirring denitrification in the step-feeding tank. NO_3^--N concentrations were statistically compared; results indicate that the effluents were significantly different ($p = 0.034$).

Higher *E. coli* removal was observed in the two-stage system than the recirculating system, with an overall average removal of 4.5 $\log_{10}$ units, conforming to the JS category B (less than 2.0 log units). Whereas, *E. coli* removal was limited with raw wastewater step-feeding application into 2 $\log_{10}$ units conforming to the JS category C.

11.4 Conclusions

The research was conducted to explore the suitability of various VFCW designs, in Jordan as a decentralized wastewater treatment plants, to produce high effluents qualities that conform to the JS 893/2006. The research has also sought to optimize the VFCWs treatment performance in order to conform to the JS for reuse in irrigation, particularly using several costless and simple operational modifications.

The recirculating VFCW and two-stage VF systems have shown high removal efficiency of COD, TSS, and BOD_5 over the study period, conforming to the JS category A. Recirculating VFCW is a modified VFCW system, combing simultaneous nitrification and denitrification by recycling portion of nitrified effluent (circulation ratio 3:1) into the recirculation tank. However, effluent TN and NO_3^--N concentrations were 55 and 44 mg/L, respectively, that the system conformed to the JS category-B (TN: 70 mg/L and NO3-N: 45 mg/L) during the monitoring phase. Therefore, the system was modified by installing plastic media in the recirculation tank that attached growth increases the abundance and activity of microorganisms. TN concentration was reduced effectively of 40 mg/L, conforming to the JS category-A, whereas, NO_3^--N concentration was reduced to 37 mg/L, conforming to the JS category-B.

The two-stage VFCW system consists of two unsaturated VFCWs in series; single-pass unplanted filter followed by planted filter (*Phragmites australis*). The effluent TN and NO_3^--N concentrations did not conform to the JS of 77 and 76 mg/L, respectively, due to insufficiency of carbon source to promote denitrification (high BOD_5 removal in VFCW) during monitoring phase of the study. Thus, this system was modified by adopting raw wastewater step-feeding strategy, i.e., a specific volume of raw wastewater was mixed with the first stage effluent in the mixing tank. TN and NO_3^--N concentrations were reduced to 52 and 50 mg/L, respectively, meeting the JS category-B. However, evapotranspiration was relatively high in the two-stage VFCW (second stage planted with *Phragmites australis*) during summer, which increased the salinity of the effluent.

Acknowledgements This work was supported by funding from the German Ministry of Education and Research (BMBF) within the context of the SMART Projects (FKZ: 02WMI1080 and 02WM1355B). Noama Shareef gratefully acknowledges the International Center for Migration and Development in Germany for additional support in cooperation with Al Balqa Applied University. Ghidaa Abdallat acknowledges the Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE) and the Helmholtz Center for Environmental Research (Helmholtz-Zentrumfür Umweltforschung – UFZ) for additional funding and support during the research. And special thank goes to Dr. Nivala for her scientific support.

References

1. Tchobanoglous G, Ruppe L, Leverenz H, Darby J (2004) Decentralized wastewater management: challenges and opportunities for the twenty-first century. Water Supply 4:95–102
2. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
3. Kadlec R, Wallace S (2009) Treatment wetlands, 2nd edn. Boca Raton, CRC Press
4. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
5. Vymazal J, Brix H, Cooper PF, Haberl R, Perfler R, Laber J (1998) Removal mechanisms and types of constructed wetlands. Constructed wetlands for wastewater treatment in Europe, pp 17–66
6. Stefanakis AI, Akratos CS, Tsihrintzis VA (2014) Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment, 1st edn. Elsevier Publishing, Amsterdam
7. Stefanakis AI, Akratos CS (2016) Removal of pathogenic bacteria in constructed wetlands: mechanisms and efficiency. In: Ansari AA, Gill SS, Gill R, Lanza G, Newman L (eds) Phytoremediation, vol 4. Springer International Publishing, Switzerland, pp 327–346
8. Dotro G, Langergraber G, Molle P, Nivala J, Puigagut J, Stein O, von Sperling M (2017) Biological wastewater treatment. Volume seven: treatment wetlands. IWA Publishing, London, UK
9. Alwahaibi B, Jafary T, Al-Mamun A, Baawain MS, Aghbashio M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558
10. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380(1–3):48–65
11. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
12. Arias C, Brix H, Marti E (2005) Recycling of treated effluents enhances removal of total nitrogen in vertical flow constructed wetlands. J Environ Sci Health A 40:1431–1443
13. Brix H, Arias CA, Johansen NH (2003) Experiments in a two-stage constructed wetland system: nitrification capacity and effects of recycling on nitrogen removal, pp 237–258
14. Stefanakis AI, Akratos CS, Tsihrintzis VA (2011) Effect of wastewater step-feeding on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecol Eng 37:431–443
15. Li F, Lu L, Zheng X, Ngo HH, Liang S, Guo W, Zhang X (2014) Enhanced nitrogen removal in constructed wetlands: effects of dissolved oxygen and step-feeding. Bioresour Technol 169:395–402

16. Mohsen MS (2007) Water strategies and potential of desalination in Jordan. Desalination 203:27–46
17. MWI (2009) Jordan's water strategy, 2008–2022. Ministry of Water and Irrigation, Jordan
18. Metcalf & Eddy (2003b) Wastewater engineering: treatment and reuse
19. IWA (2011) To centralize or to decentralize: an overview of the most recent trends in wastewater treatment management. The 10th Specialized Conference on Small Water and Wastewater Systems and 4th Conference on Decentralized Water and Wastewater International Network. 18th–22nd April 2011, Venice, Italy, Journal of Environmental Management
20. Echchelh A, Hess T, Sakrabani R, Prigent S, Stefanakis AI (2021) Towards agro-environmentally sustainable irrigation with treated produced water in hyper-arid environments. Agric Water Manag 243:106449
21. Mara D (2013) Domestic wastewater treatment in developing countries. Routledge, London. https://doi.org/10.4324/9781849771023
22. Guest JS, Skerlos SJ, Barnard JL, Beck MB, Daigger GT, Hilger H, Jackson SJ, Karvazy K, Kelly L, Macpherson L (2009) A new planning and design paradigm to achieve sustainable resource recovery from wastewater 1. Environ Sci Technol 43:6126–6130
23. JISM (2006) Jordanian institute of standards and metrology. Amman, Jordan. Jordanian Standards and Guidelines for Reuse in Irrigation in the Hashemite Kingdom of Jordan
24. Nivala J, Abdallat G, Aubron T, Al-Zreiqat I, Abbassi B, Wu GM et al (2019) Vertical flow constructed wetlands for decentralized wastewater treatment in Jordan: optimization of total nitrogen removal. Sci Total Environ 671:495–504
25. Al-Zreiqat (2013) Optimization of the recirculating vertical flow constructed wetland for Total nitrogen removal. Master Thesis, Al-Balqa Applied University, Al-Salt, Jordan
26. Shareef N (2019) Innovation Technologies in Wastewater Treatment: a cost-effective solution -Jordan, chapter 15. Springer International Publishing. https://doi.org/10.1007/978-3-030-18350-9_1
27. Bratbak G, Dundas I (1984) Bacterial dry matter content and biomass estimations. Appl Environ Microbiol 48(4):755–757
28. Nouvion B, Faup (1987) Effect of biomass quantity and activity on TOC removal in a fixed-bed reactor. Wat Res 21:35–40
29. APHA (1995) Standard method for examination of water and wastewater. Water environment federation, 19th edn. American Public Health Association, Washington DC
30. Kadlec RH, Knight RL, Vymazal J, Brix H, Cooper P, Haberl R (2000) Constructed wetlands for pollution control: processes, performance, design and operation. IWA scientific and technical report 8, London
31. Brix H, Arias CA (2005b) The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: new Danish guidelines. Ecol Eng 25:491–500
32. Saeed T, Sun G (2012) A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: dependency on environmental parameters, operating conditions and supporting media. Environ Manag 112:429–448
33. Metcalf & Eddy (1991) Wastewater engineering: treatment, disposal and reuse. MacGraw-Hill, New York
34. Bitton G (1994) Wastewater microbiology. Wiley-Liss, New York

Chapter 12
Constructed Wetlands for Sustainable Wastewater Treatment in Oman: Experiences from Research and Case Studies

Alexandros Stefanakis

Abstract Many countries and regions under hot and arid climates suffer from an always growing pressure on their limited freshwater resources, which are also continuously degrading. Despite the increasing water scarcity, water demand is also increasing resulting in over-exploitation of the limited freshwater resources. At the same time, wastewater is still largely viewed as a waste and is discharged to the environment, even without proper treatment. Wastewater management and reuse could be a new water source in the local and regional water balance in these regions, particularly in the Middle East, one of the most water-stressed regions in the world. For this, sustainable and effective solutions that can be adopted to the local climatic, institutional, cultural, and economic conditions are needed. Therefore, the sustainable treatment technology of Constructed Wetlands is viewed as an ideal nature-based solution for wastewater management. This chapter provides a summary of the current experiences of Constructed Wetlands technology in the Sultanate of Oman. Case studies for different applications (municipal and industrial wastewater) are presented in order to highlight the technical feasibility of this technology under the hot and arid climate of the Middle East.

Keywords Wastewater treatment · Constructed wetlands · Vertical flow · Horizontal flow · Surface flow · Nature-based solutions · Middle East · Oman · Hot and arid climate · Sustainability · Reuse

---

A. Stefanakis (✉)
Laboratory of Environmental Engineering and Management, School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece

EURECA-PRO – The European University on Responsible Consumption and Production, Chania, Greece
e-mail: astefanakis@tuc.gr

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_12

12.1 Introduction

Although the majority of Earth's surface is covered by water, yet this natural resource remains largely at risk while humans and ecosystems crucially depend on it. The extend of drylands, i.e., areas with low to zero freshwater availability, is already estimated to an cover approximately 45% of the Earth's terrestrial area [1]. The water crisis that is now evident in many parts of the world could be seen as part of the global environmental or climate crisis due to the global climate change that is already causing irreversible harm to humans, the built environment, and the biosphere [2, 3]. This changing environment has inevitably affected the water cycle (global and regional) resulting in increasing water variability. Some regions experience frequent extreme precipitation and flooding events, others suffer from extended droughts, while both extreme events may appear in the same region over a year. 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, with annual precipitation below 250 mm, and in many desert areas, as little as 50 mm [4]. Most of the countries in the region are classified as arid or hyper-arid areas with extreme freshwater scarcity [1, 5], while all countries in the region are anticipated to enter that group by 2050 [6].

In addition, human demographics and land use is also changing dramatically; today, more than 55% of the world's population is living in cities, a figure which is projected to raise up to 68% by 2050 [7]. The progressing climate change is also putting a continuous pressure on existing infrastructure, deteriorating its status [3, 8]. As the urban areas grow in both size and number, so does the need for resources and services as well as the extend of pollution and the necessity for environmental protection.

These challenges cannot be effectively addressed with the current approach of expanding grey infrastructure with non-renewable materials such as concrete, stone and asphalt; thus, new solutions are needed to support a sustainable growth based on a wiser extraction and use of natural resources as it is the main principle of circular economy [9, 10]. In this framework, nature-based solutions (NBS) a crucial component in the new economic model that can be applied in both urban (where is probably more needed) and rural areas [3, 11]. NBS can be a key part of the plan to address the climate change impact and to increase the resilience of the ecosystems via circular economy strategies, i.e., effluents reuse, to close the loop of materials and energy flows and eliminate waste generation [74]. NBS as ecological engineering solutions [12] can be installed in a densely populated city where green areas can be built and/or created on top of the existing or new infrastructure, e.g., a park on top of a parking garage, or an urban garden on top of a school or a green roof [13]. Such solutions provide a different approach and bring new ideas to water and wastewater management.

NBS have a particular role to play in areas with extreme water scarcity such as the Middle East. This region is facing all the global challenges at the same time, from the rapid urbanization and population growth to the above-mentioned overexploitation of the limited freshwater resources [14]. On the other hand, the per capita water consumption rate in the region is among the highest in the world, which implies that changes in the food-water-energy nexus are urgently needed [15], while only 40% of the region's wastewater is currently treated [16]. It is characteristic that in the richer parts of the Gulf Cooperation Council countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates), 84% of the wastewater is collected and treated to secondary and tertiary stages, but less than 15% of it is reused [17]. This means that a different way of thinking and a paradigm shift is needed in the way that water resources are managed in the region. For example, despite the apparent opportunities of wastewater reuse, there is a minimum valorization of this option due to a variety of technological, institutional, economic and cultural local and regional barriers [14, 18]. Considering these, a technological solution that would overcome all these barriers and provide answers to the local and global challenges has a great potential in this region. Therefore, the nature-based Constructed Wetlands (CW) technology could be a key NBS for sustainable wastewater treatment reuse in the Middle East.

The technology of CW is not a new technological development and is already widely used in Europe, north America and Australia, but rarely applied in the Middle East, despite its tremendous potential, especially under the climatic and social context of the region [14]. As an established treatment technology, CW have been successfully applied not only for municipal wastewater [19, 20] but also for various industrial effluents [21] such as olive mill wastewater [22], cork processing wastewater [23, 24], tanneries [25], hydrocarbons contaminated waters [26–28], glass industry wastewater [29] and dairy effluent [30].

The advantages of CW systems are well documented and extend to environmental, economic, technical and social benefits [20, 31], from water purification to flood and stormwater control, ecosystem services, habitat creation, low-cost operation, simple and easy operation and maintenance, all without the need for chemicals and with minimum energy input demand. These benefits can be particularly harnessed in the Middle East region, since the climatic conditions are favorable for the development of CW solutions [14]. However, challenges such as the higher area demand compared to mechanical technologies or the higher evapotranspiration rates are currently under investigation and new designs are already addressing these limitations.

It is difficult to estimate the number of CW facilities in the Middle Eastern region but it is safe to say that the numbers are relatively small. In most countries in the region, there are probably less than 10 systems, while in few others, there can be one or two dozens of pilot or full-scale CW facilities of various sizes. Therefore, the goal of this chapter is to present some notable CW facilities and case studies in the Middle East that have been applied either for research purposes or as operational facilities for different wastewater sources (municipal and industrial). Ultimately, the objective of this chapter, in accordance to the book scope, is to demonstrate that different wastewater treatment (municipal and industrial) plants and CW designs have been and can be successfully implemented under the specific climatic conditions of the Middle East.

12.2 Horizontal Subsurface Flow Constructed Wetland for Onsite Domestic Wastewater Treatment

One of the simplest applications of CW technology is to treat onsite the domestic wastewater derived from a single household or small communities. Such an exemplary case is demonstrated by a research facility developed by the German University of Technology in Oman (GUtech) and the Research Council of the Sultanate of Oman in 2011 [32]. This project called 'EcoHaus' is built as a net-zero-energy residential building on the GUtech campus [33]. The EcoHaus covers 250 m^2 and serves as a guesthouse. As part of the ecological building approach, an onsite CW system was built (Fig. 12.1) to receive and treat all sewerage (black and grey) water, as a cost-effective and sustainable treatment solution allowing for the reuse of the treated effluent for garden irrigation [14].

The design flow rate of the CW is 1 m^3/day, equivalent to 5 population equivalent (PE) [14, 32]. Wastewater from the EcoHaus flows by gravity into a covered septic tank (5 m^3) for primary treatment, i.e., settling of solids and flotation of fats and oils. Then the septic tank effluent overflows to a HFCW (15 m^2). The water level in the HFCW is maintained few cm below the gravel surface, hence preventing this way any odors, mosquito development and potential contact of wastewater with humans or wildlife. In 2019, the CW was replanted with local common reeds (*Phragmites australis*), while irrigation of local trees and shrubs were irrigated with the treated effluent. This demonstration CW system has zero energy input demand and minimum maintenance requirements. It shows in a simple but clear way how wetland technology can be a green and easy solution for onsite wastewater management for single households in the Middle East.

Fig. 12.1 The circle-shaped Ecohaus and the demonstration horizontal flow CW for onsite wastewater management and the reuse irrigation field at the the German University of Technology in Oman

12.3 Vertical Flow Constructed Wetland for Municipal Wastewater Treatment

While there are many CW designs, vertical flow CWs (VFCWs) are among the most widely used over the last 20 years [19]. Typically, wastewater is loaded intermittently loaded wastewater on top of the bed across its entire surface to percolate by gravity through the porous media, reaching a bottom drainage pipe network [34]. A specific design comprises only gravel as filter media in the first stage VFCW bed, which allows the feeding of pre-screened raw wastewater without the need for primary treatment. This is also known as the French system [31]. Due to this feeding regime, the VFCW bed is mostly an aerobic system that promotes organic matter biodegradation and nitrification [19]. However, this also means that denitrification is not favored, thus limiting total nitrogen removal [35]. To increase nitrate removal, hybrid CW systems have been used where the VFCW is combined with a horizontal subsurface flow CW (HSFCW) [36]. However, this option increases the initial investment. Therefore, cost-effective modifications are required to improve the total nitrogen removal in VFCWs.

Effluent recirculation is one modification that has been studied in single and hybrid CWs [37]. Typically, an upstream anoxic tank is used to recirculate the nitrate-rich effluent of the VFCW [38] in order to increase the contact time between denitrifying microorganisms and the treated effluent. Another modification is wastewater step-feeding, i.e., wastewater feeding into the CW at more than one inflow point [39]. Step-feeding adds small volumes of raw wastewater along the wetland length or in the downstream stage to increase the carbon availability and has been tested in single-stage HSFCW [40] and multi-stage VFCWs [41]. Finally, the increase in carbon availability for denitrification has also been tested by adding an external source of carbon [42].

In order to optimize the two-stage VFCW system, a full-scale experimental facility was built in Oman by Haya Water (the governmental authority for wastewater management) [43]. Specific objectives were to test the efficiency of such a system with effluent recirculation under the hot and arid climate of the Middle East, to apply and evaluate various operational modifications for improved total nitrogen removal, and to assess the overall performance improvement in terms of total nitrogen removal and compliance with the prevailing legal standards. This study presents optimized design and operation guidelines for a modified French CW system, i.e., a two-stage VFCW, under a hot and arid climate to provide a treated effluent that will comply with strict Class A irrigation standards in Oman [44]. It should be mentioned that this was the first study of this kind in the Middle East and also one of the few at an international level to test all these modifications combined.

The research facility (Fig. 12.2) is located in Quriyat city (45,000 residents) in Oman and comprised two stages of VFCW beds equipped with a modified substrate media composition, and with 100% effluent recirculation. The plot area was 1300 m^2, of which 995 m^2 was the net wetland area [43]. The first stage VFCW (VF1) consisted of three parallel beds with a surface area of 123 m^2 each, while the

Fig. 12.2 Aerial view of the experimental VFCW system in Quriyat, Oman

second stage VFCW (VF2) consisted of two parallel beds, each 312.5 m^2 in area. An anoxic tank (AT) equipped with a submersible mixer allowed for up to 100% recirculation of the treated effluent (TE) after the VF2 beds. The effluent recirculation rate was gradually increased from 50% to 100% during the first two operational months. The design inflow was 50 m^3/d, i.e., 25 m^3/d of raw wastewater and 25 m^3/d of recirculated effluent (at 100% recirculation rate), with an average hydraulic loading rate (HLR) of 0.135 m/d (considering only the area of the VF1 beds). The substrate media in VF1 beds consisted of a 35 cm-thick washed sand layer on top of a 20 cm-thick fine gravel layer, while the same media was used in the VF2 beds with respective thicknesses of 65 and 20 cm. Coarse sand was used at the top of the first stage VFCW bed to avoid infiltration of fine solids in the bed matrix. Each bed was equipped with a drainage control manhole that allowed the water level adjustment and was lined with a polyethylene liner (1.5 mm). All VFCW beds were planted with native common reeds (*Phragmites australis*).

The first experimental period focused on the evaluation of the treatment performance with 100% effluent recirculation with the schematic overview shown in Fig. 12.3 [43]. The wastewater was discharged into a buffer tank that fed the AT, providing a hydraulic retention time (HRT) of 2 h. The wastewater was loaded through vertical distribution pipes on the VF1 beds (one operational bed per day; alternate feeding regime). The drained water was collected by the drainage pipes in the VF1 stage and was discharged by gravity to the second stage pump station that fed the VF2 beds through 14 spray nozzles per bed to optimize the wastewater distribution across the bed surface and the aeration of the bed matrix. The TE from the VF2 beds was collected to the recirculation tank (RT). Disinfection took place in the TE tank through the dosing of sodium hypochlorite.

During the second phase, various modifications were tested [43]. The first (M1) was the extension of the HRT in the AT to enhance the growth rate of denitrifying bacteria and extend the contact time between them and the wastewater. The second (M2) was the increase of the HRT in the VF2 beds by switching off the recirculation

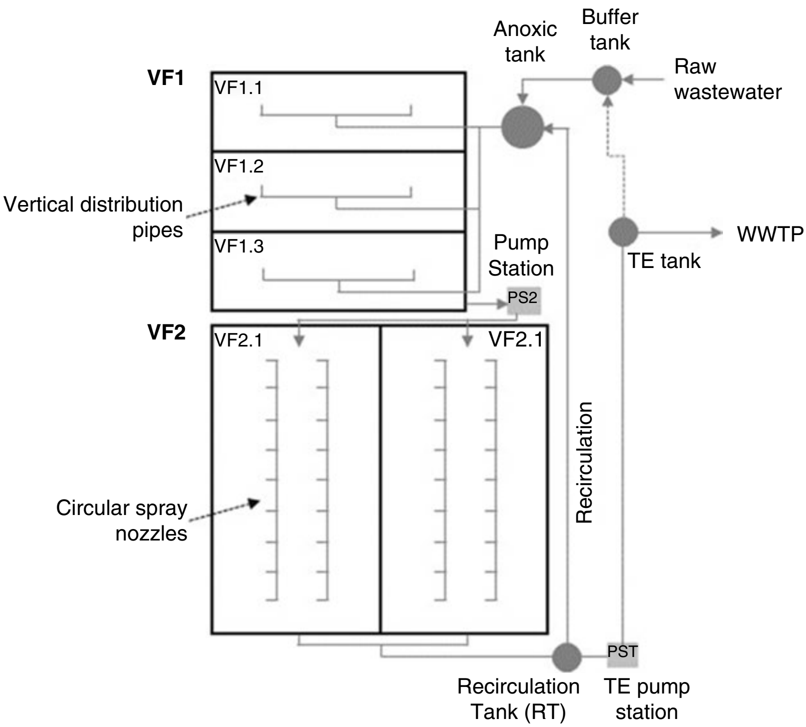


Fig. 12.3 Schematic overview of the full-scale VFCW system in Oman (PS: Pump station; TE: Treated effluent) [43]

pump and increasing the saturation level within the VF2 beds to reach an impoundment up to 30 cm below the media surface. The third (M3) was removing the spray nozzles in the VF2 beds to reduce the oxygen supply in the beds and assist in the creation of anaerobic conditions within the wetland body. The fourth (M4) was the step-feeding of raw wastewater to the second stage pump station as well as of methanol as an alternative in order to provide an external carbon source to promote denitrification.

Table 12.1 shows the overall performance during the first experimental phase [43] As the results show, the VFCW with 100% recirculation managed to comply with almost all parameters required in the national irrigation standard. TKN and NH_4-N levels were decreased to 1.23 and 0.28 mg/L in the outflow (98.57% and 99.52% removal; Table 12.1), respectively, indicating strong nitrification in the system. The main limitation remained TN removal through denitrification. The VF1 bed effluent showed that most of the organic matter (BOD_5 < 10 mg/L and COD<100 mg/L) and nitrogen (ammonia nitrogen and TKN) removal took place in the first stage, and the first stage could already achieve full nitrification (average NH_4-N of 0.5 mg/L) but with a nitrified effluent (average of 76.5 mg/L NO_3-N). Hence, the VFCW provided an average NO_3-N effluent of 22.5 mg/L in the first

Table 12.1 Average and standard deviation parameters of influent and effluent pollutants concentration and respective removal efficiencies in the VFCW during the first experimental phase [43]

Parameter	Influent	Effluent	Removal	Irrigation standard A
	Aver ± sd		%	
Temperature (°C)	27.6 ± 1.9	27.1 ± 1.9	–	–
pH (−)	7.11 ± 0.2	7.94 ± 0.31		6–9
EC (mS/cm)	2.7 ± 0.5	5.2 ± 1.4		2.0
TDS (mg/L)	1462.9 ± 254	1742 ± 474	–	1500
TSS (mg/L)	527 ± 232	1.9 ± 1.5	99.57	15
BOD_5 (mg/L)	337 ± 122	3.9 ± 0.3	98.68	15
COD (mg/L)	971 ± 337	18.8 ± 7.5	97.84	150
TN (mg/L)	147 ± 12	25.0 ± 15	82.98	–
TKN (mg/L)	87.6 ± 10.8	1.2 ± 0.7	98.57	5
NH_4-N (mg/L)	58.7 ± 8.4	0.28 ± 0.3	99.52	5
NO_3-N (mg/L)	0.15 ± 0.34	22.5 ± 14.8	–	50 (as NO_3) [11.3 as N]
TP (mg/L)	11.6 ± 2.3	0.31 ± 0.47	97.17	30
FOG (mg/L)	30.9 ± 60.0	0.30 ± 0.1	98.64	0.50
FC (log10 MPN/100 mL)	8.2 ± 0.5	1.62 ± 0.6	99.99	2.3
VHO (Ova/L)	25.4 ± 39.6	0.30 ± 0.4	100.0	<1

phase, resulting in an effluent TN value (25 mg/L; Table 12.1) higher than the Omani Standard for reuse [44]. This was the main issue during the first phase of this study that indicated the need for additional actions to improve the denitrification rate.

The second phase focused on the optimum modification or combination of modifications to increase the nitrate removal in the VFCW [43]. The first modification, i.e., the extension of the HRT in the AT from 2 to 5 h, was tested for 2 months and resulted in a slight decrease in effluent NO_3-N from 25 to 20 mg/L. During the second modification, the recirculation pump was switched off, and the water level in the VF2 beds was increased to 30 cm below the porous media surface, extending the HRT inside the VF2 beds to 3 days. However, this showed a negative effect since the effluent nitrate increased to 70 mg NO_3-N/L, probably due to the limited BOD in the VF1 beds effluent, which is also required for denitrification to take place. This indicated that recirculation had the most substantial effect on the enhancement of denitrification, thus the system was restored to the previous operational mode, i.e., 100% recirculation. The spray nozzles for wastewater distribution in the VF2 beds were removed (M3) to assist the establishment of anaerobic conditions in the VF2 bed (the water level remained at 30 cm below the porous media surface) and a gradual reduction of the effluent NO_3-N was immediately measured until it stabilized around 11 mg/L. Although this value was slightly below the limit value (11.3 mg/L), step-feeding was also tested [43]. Considering the minimum BOD/N ratio of 4:1 required for denitrification, it was calculated that almost 6 m^3/d of raw wastewater would be required to provide an additional nitrate removal of 10 mg/L. This volume was pumped directly into the second stage pump station, but since it was not considered in the design of the VFCW, the existing pump capacity could not handle the additional volume. It was then decided to simulate step-feeding with the addition of an artificial carbon source (methanol; 792 g COD/L) into the second stage pump station. Within 2 weeks after starting the methanol dosing, NO_3-N dropped from 49.2 mg/L to 0.2 mg/L in the VF1 effluent and from 59 mg/L to 1,65 mg/L in the VF2 effluent [43].

This study of a full-scale experimental VFCW system in the Middle East over a period of 18 months, testing different operational modifications, showed that this system can be very effective providing complete organic matter biodegradation and nitrification. The adoption of 100% effluent recirculation along with step-feeding, either with raw wastewater dosing into the second stage or by artificial carbon dosing provided an effluent quality that complied with all limit values of the Oman Irrigation Standard A, including TN. This study demonstrated that with further optimization of the passive VFCW system, high rates of nitrification and denitrification are possible. The tested CW system proved feasible for hot and arid climates and can provide an effluent quality appropriate for irrigation with low overall operational costs. It should be noted that this study was awarded the Annual Research Award 2021 by the Ministry of Higher Education, Research and Innovation of Oman.

12.4 Aerated Constructed Wetland for Municipal Wastewater Treatment

In order to further reduce the area demand, the aerated CW design has lately been developed [45]. In this design, air is provided from an external aeration device (e.g., a side blower) to increase the oxygen supply and establish aerobic conditions that enhance the aerobic process, thus significantly reducing the system footprint and increasing the treatment capacity [46, 47], while still using significantly less energy per m^3 wastewater treated than conventional wastewater treatment plants. Aeration in subsurface flow CWs can be implemented with uniform distribution of small air quantities across the bottom of the bed. The combined action of the vertical/horizontal movement of the wastewater and the upflow movement of air bubbles results in a very good mixing of air and wastewater in the bed [48]. Artificial aeration has a much higher treatment capacity than passive wetlands with significantly reduced area requirements [42, 47], reaching high levels of organics degradation and nitrification. Aerated wetland technology is mostly applied under temperate and cold climates so far [47], while in hot and arid climates there is only a very limited number of research [35] and full-scale systems.

One of the first full-scale aerated CW in the Middle East was built in Oman in 2018 under desert environmental conditions [14, 49]. The area suffers from frequent sandstorms incidents, while the atmosphere can be laden with airborne dust particles (even <2 microns). The daily average temperature exceeds 40 °C in summer and reaches up to 30 °C in winter, while annual rainfall is almost negligible.

This CW is treating domestic wastewater from a medium-sized community of approx. 1800 persons, generating an inflow of 350 m^3/day [49]. The wastewater includes wastewater from the residential and accommodation areas as well as flows from offices and kitchen facilities. Raw wastewater is collected in a lifting station in the settlement, and after simple screening (coarse screen) it is pumped to the new CW facility. The CW is located approx. 150 m away from the closest community buildings. The CW facility is designed for a final treated effluent that complies with the irrigation standards of Oman (Class A), in order to reuse the treated effluent for irrigation of green public areas at the settlement.

The first stage is a VFCW system, and the second stage is the Aerated Constructed Wetland (ACW) with horizontal subsurface flow. Figure 12.4 shows a view of the ACW bed 1 month after planting. The VFCW has a surface of 2100 m^2 and is separated into three parallel cells. Each day, only one cell receives the raw wastewater, thus intermittent loading is applied, and the feeding cycle comprises feeding (1–2 days) and resting periods (2–4 days). The operational cycle is controlled by manual valves located at the front-end of the VFCW. As for the French system described before, this setup avoids a primary sedimentation stage. The VFCW basin has a total depth of 1 m, of which 65 cm from the bottom is the gravel layer. The bottom of the bed is lined with an HDPE membrane (1.5 mm) [49].

The second stage ACW has a surface of 800 m^2 and receives the partially treated water of the first-stage VFCW by gravity, providing the final desired quality [14]. Step-feeding of raw wastewater is also applied, with a small volume routed to the ACW to provide an additional carbon source for denitrification. The practice of wastewater step-feeding has been found to improve the treatment performance in HSFCWs [39]. The total depth of the bed is 1.3 m, of which 1 m is the depth of the gravel media layer. The ACW is also lined with an HDPE membrane. Artificial aeration is provided through a network of aeration drip lines placed at the bottom of the bed connected to a side-channel blower (1 working, 1 stand-by) that delivers an

Fig. 12.4 The aerated Constructed Wetland in Oman during the start-up phase

airflow of 330 m^3/hr. [49]. The aeration pipes are placed at short distances at the bottom, providing small bubbles of air in the saturated gravel layer to enhance the aerobic processes. The water level is adjustable through a water level control device and is set few centimeters below the surface of the gravel layer. The ACW effluent is collected through a perforated pipe placed at the bottom of the bed above the HDPE liner along the downstream width side.

Both CW stages are planted with native wetland plant species. The VFCW bed is planted with common reeds (*Phragmites australis*) and the ACW is a polyculture of *Typha domingensis*, *Schoenoplectus littoralis* and *Cyperus laevigatus* [14]. The ACW effluent is collected by gravity in a pumping station, where pumps push the treated effluent through a UV unit with a 30 m^3/hr. capacity for final disinfection. The final effluent is further pumped and reused for irrigation of green spaces in the adjacent settlement.

Table 12.2 shows the overall efficiency of this facility for the first operational months [49]. This novel CW has a comparatively low area requirements (1.6 m^2/PE) showcasing the current advances in wetland technology that enable the implementation of CW even in areas with limited available land. As the table shows, the effluent quality complies with the national irrigation standards (Table 12.2). Most of the organic solids are retained, as indicated by the low effluent TSS. The system reached almost complete organic matter degradation and nitrification, due to the high oxygen supply via the artificial aeration that favours aerobic microbial activity.

Ammonia nitrogen removal was almost complete and stable. Nitrification is an aerobic process and is enhanced by the higher oxygen supply via the artificial aeration. The ambient temperature in this environment is also ideal for nitrification, since this process has an optimum temperature range between 25–35 °C [19]. In

Table 12.2 Average influent and effluent concentrations and removal rates of the various physicochemical parameters during the first operational months. (nd = not detected) [49]

Parameter	Influent	Effluent	Removal (%)
BOD_5 (mg/L)	213	2	99.0
COD (mg/L)	534	24	95.1
TSS (mg/L)	98.2	3.0	96.8
Total nitrogen – TN (mg/L)	50.8	17.5	66.4
Ammonia nitrogen – NH_3-N (mg/L)	38.1	0.1	99.7
Total Kjeldahl nitrogen – TKN (mg/L)	39.4	0.5	98.7
Nitrate nitrogen – NO_3-N (mg/L)	0.6	16.4	–
Total phosphorus – TP (mg/L)	20.6	3.1	85.9
pH (−)	7.1	8.0	–
Electrical conductivity – EC (μS/cm)	1125	1492	–
Total dissolved solids – TDS (mg/L)	678	932	–
Total coliform – TC (CFU/100 mL)	962	nd	100
Faecal coliform – FC (CFU/100 mL)	720	nd	100
Intestinal helminth/nematode eggs (eggs/L)	57	nd	100
Dissolved and emulsified oil (mg/L)	20.5	<10	–

addition, it is also noteworthy that nitrate effluent concentration remained below the discharge limit. This implies that despite the aerobic conditions in the system and the almost complete nitrification, nitrate removal also takes place (denitrification). This interesting result has also been found in other studies using a similar setup [50, 51]. Denitrification is an anaerobic process and sufficient organic carbon supply is crucial for nitrate reduction as an energy source for denitrifying microorganisms. In this design, sufficient carbon supply is maintained through the step-feeding of raw wastewater to the ACW, which apparently contributes to the nitrate transformation. Additionally, the aeration regime possibly alters the microbial community composition and characteristics, enabling nitrate removal even under these conditions. Such changes in the operational mode and even wastewater composition have been found to impact the microbial community composition and patterns [26]. Further investigation on this issue will provide better insight into the processes taking place within the system. Finally, disinfection was also effective since no microbiological contamination was detected in the treated effluent.

This full-scale CW facility is one of the first in Middle East with such an advanced design that combines a VFCW with a novel Aerated CW providing sludge accumulation and mineralization along with an effluent quality appropriate for irrigation reuse. Furthermore, this CW design has one of the lowest area demands compared to passive wetland systems. This design is particularly attractive for areas with limited space availability and has a higher treatment capacity too. The overall performance of this facility proves its effectiveness even under hot and arid areas.

12.5 Surface Flow Constructed Wetland for Oily Produced Water Treatment

One of the mainstream applications of CW technology is in the oil and gas sector. The exploration activities for oil and gas production result in a polluted water volume that is one of the largest industrial waste streams worldwide [52]. This polluted water occurs during the crude oil recovery as well as during other forms of fossil energy recovery such as shale gas, oil sands and coal bed methane [53]. This oily wastewater, which is known as produced water, is essentially a co-product of oil production in many countries. This water typically contains residual hydrocarbons, salts and various organic and inorganic compounds (e.g., emulsion breakers, chemical additives, solvents, heavy metals etc.), which prohibit the discharge of this wastewater to the environment [54].

The most widely applied management practice of this oily wastewater is disposal into deep wells (DWD) or into the ocean (for offshore production activities), while smaller volumes can be re-injected into reservoirs to maintain pressure for the oil wells [55]. However, there methods are undesirable due to the related environmental risk and the high operational costs. Various mechanical and chemical technologies have been used to treat this water, e.g., membrane filtration [53, 56], thermal technologies [57], flotation [57] and electrocoagulation [58]. However, most of these technologies possess high operation and maintenance costs, require a high energy input, and face frequent mechanical failures. In particular, the implementation of such technologies in remote areas (where most of the oil resources are located) is often problematic due to the high cost, lack of local expertise and poor governance [59].

Considering the above, CW appear as a promising treatment technology for produced water management bringing the benefits of nature-based solutions to the oil and gas industry. It is already reported that CW can be effectively applied for the remediation of waters containing petroleum hydrocarbons, related additives and phenols [26, 28, 60, 61]. However, there are only few CW systems in facilities related to oil production and processing, e.g., refineries and oil and gas fields [26, 62] and few others in the USA [63], in Sudan [64] and in China [65]. One of the largest CW systems worldwide was built in Oman for the treatment of oily produced water [14, 66, 67].

This facility is located at an oilfield in South Oman where deep well disposal of the oily produced water is applied. The climate in the area is a desert climate, with an average air temperature exceeding 50 °C in summer, while rainfall is practically negligible. The governmental oil company (Petroleum Development Oman) started the implementation of the project in 2008 [66], and the operation started in late 2010 with an initial treatment capacity of 45,000 m^3/day. After three expansion phases, today this CW system treats 175,000 m^3/day or one million barrels of polluted water [14], a volume that equals the sewage produced daily by a city of a million people. The CW system covers of 490 hectares of Surface Flow CW and 780 hectares of evaporation ponds (EPs), thus being one of the world's largest CW (Fig. 12.5). The oily wastewater first passes through an oil separation and recovery step using passive hydro-cyclones utilizing the inherent hydraulic pressure in the pipeline without the use of additional energy or chemicals before its discharge with gravity to the CW beds. No pumps are used in the facility and the treated water is discharged into

Fig. 12.5 Aerial view of the Constructed Wetland facility for oily produced water treatment in Oman. (Courtesy: Bauer Resources GmbH)

the evaporation ponds, resulting in salt formation that is processed into industrial grade salt [66].

The CW beds are sealed with a mineral layer made of locally available clay to avoid the usual High-Density Polyethylene (HDPE) liner and are planted with local plant species, i.e., *Phragmites australis*, *Typha domingensis*, *Schoenoplectus littoralis*, *Juncus rigidus* and *Cyperus spp*., to enhance the biomass production and the resilience of the ecosystem, making this CW system a polyculture [66, 67].

The inflow produced water is brackish with total dissolved solids exceeding 7000 mg/L [66] and an Oil in Water (OiW) concentration of approx. 350 mg/L (but can exceed 500 mg/L instantly), but is poor in nutrients, i.e., total nitrogen and phosphorus concentrations below 2.5 mg/L. More than 85% of the oil content is recovered by the passive hydrocyclones and skimmers, so that and the residual oil hydrocarbons (on average 30–50 ppm) can be discharged with gravity to the CW beds, where it is biologically degraded, producing an effluent that complies with the national limit value (<0.5 mg OiW/L) [14, 66]. Studies have shown that the CW rhizosphere is rich in hydrocarbon-degrading bacteria [68], which play the key role in the high oil removal rate. Moreover, the reed stems act as a physical filter for trapping floating oil that is then biodegraded.

Since this CW started its operation, five deep well disposal pumps are shut down as a consequence. Considering also that the CW is a gravity-based system with almost zero energy consumption, the CW presents a significant reduction of the carbon emissions that reaches 99% compared to the other management options [66, 69]. In the first ten years its operation, the amount of carbon dioxide emissions saved is estimated at 1.275 million tonnes, equivalent to the emissions by 25,000 cars over a 10-year period. It is also characteristic that the large CW system and the ponds created a valuable new habitat for migratory and resident birds and other wildlife, since more than 130 migratory bird species use this facility as a stop-over between Asia and Africa.

The clean effluent provided by this CW system allows to explore several possibilities to further optimize the whole management process by adopting circular solutions [67, 70]. The treated effluent can be reused in irrigation, a practice that is of high value in hot and arid climates [71]. However, considering that the effluent remains brackish, the selection of plants should be carefully considered. A research study was carried out in this CW, where various salt tolerant plants were tested at a large irrigation field of 22 hectares [66, 72]. The selected crops, e.g., biofuel producing plants and cotton plants, had a related market value. The output of this research project showed that this treated effluent could be indeed valorized for the irrigation of commercial plants. Additional tests are carried out on the use of the reed biomass for compost production and biogas generation, in order to completely close the loop of materials and waste, and promote circularity in this large-scale CW application [70].

Additionally, this large CW system provides a wide range of ecosystem services. A study evaluated the effect of the CW on the local microclimate, revealing for the first time that the CW beds regulated the local microclimate [73]; a temperature reduction by 10 °C was found between the CW body and a perimeter of up to 1 km

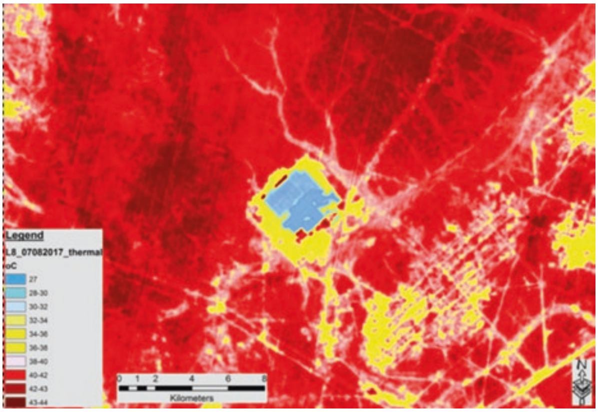


Fig. 12.6 Surface temperature variations in the CW facility (light blue) in Oman and its perimeter

distance (Fig. 12.6), indicating the positive effect of the CW on its surrounding environment. Such findings are very helpful as it can also give insight on the potential to modify the local biodiversity and reduce the energy consumption for cooling.

12.6 Conclusions

Proper wastewater management in hot and arid climates is still a challenge considering the climatic, institutional, financial, and cultural context in each country. Regions with such a climate suffer from steadily deteriorating freshwater sources and scarcity, while at the moment the only solution appears to be the expensive, energy-intensive and unsustainable desalination process to cover their needs. The Middle East, being one of the most water scarce areas in the world, still lacks effective and universal wastewater management and reuse practices due to a variety of institutional, technical, economic, and cultural barriers. The sustainable, nature-based technology of Constructed Wetlands is as an ideal wastewater treatment solution for hot and arid climates, such as in the Middle East, that can provide a feasible solution within the local context of the various countries in the region. To date, Constructed Wetlands remain largely a relatively unknown technology in the Middle East. However, despite the limited market penetration of CW in the region, successful projects and some unique case studies can be found in the region. This chapter presented different CW applications for domestic, municipal and industrial wastewater treatment in the Middle East region, at different scales. The existing case studies demonstrate not only the technical efficiency and feasibility but also the sustainable character of this treatment technology that can be easily implemented under these climatic conditions, while also providing further options for a circular management of the treated effluents, e.g., reuse in agriculture. Constructed Wetlands are already a proven technology in the region, even in large scale, and can be a feasible solution for wastewater treatment in hot and arid climates, providing additional ecosystem services and contributing to water conservation and climate change mitigation.

References

1. Pravalie R (2016) Drylands extent and environmental issues. A global approach. Earth-Sci Rev 161:259–278
2. IPCC (2015) Intergovernmental Panel on Climate Change. Available from: https://www.ipcc.ch/. Accessed 15 Dec 2020
3. Stefanakis AI, Calheiros CS, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sust 1:303–318. https://doi.org/10.1007/s43615-021-00022-3
4. FAO – Food and Agriculture Organization of the United Nations. AQUASTAT Database (2014) Available online: http://www.fao.org/ag/agl/aglw/aquastat/dbase/index.stm. Accessed 12 Mar 2020
5. World Resources Institute (2019) Available online: https://www.wri.org/aqueduct. Accessed 10 June 2020
6. United Nations. World Population Prospects: The 2008 Revision. Available online: http://www.un.org/esa/population. Accessed 26 Dec 2019
7. United Nations (2019) World urbanization prospects. Department of Economic and Social Affairs. ST/ESA/SER.A/423
8. Perera D, Smakhtin V, Williams S, North T, Curry A (2021) Ageing water storage infrastructure: an emerging global risk. UNU-INWEH Report Series, Issue 11. United Nations University Institute for Water, Environment and Health, Hamilton, Canada
9. Nikolaou IE, Jones N, Stefanakis A (2021) Circular economy and sustainability: the past, the present and the future directions. Circ Econ Sust 1:1–20. https://doi.org/10.1007/s43615-021-00030-3
10. Stefanakis AI, Nikolaou I (2021) Circular economy and sustainability, vol volume 1. Elsevier Publishing, Amsterdam, Netherlands
11. Atanasova N, Castellar JA, Pineda-Martos R, Nika CE, Katsou E, Istenič D, Pucher B, Andreucci MB, Langergraber G (2021) Nature-based solutions and circularity in cities. Circ Econ Sust 1:319–332. https://doi.org/10.1007/s43615-021-00024-1
12. Schönborn A, Junge R (2021) Redefining ecological engineering in the context of circular economy and sustainable development. Circ Econ Sust 1:375–394. https://doi.org/10.1007/s43615-021-00023-2
13. Calheiros CSC, Stefanakis AI (2021) Green roofs towards circular and resilient cities. Circ Econ Sust 1:395–411. https://doi.org/10.1007/s43615-021-00033-0
14. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
15. Ibrahim AJ, Shirazi NS (2021) Energy-water-environment nexus and the transition towards a circular economy: the case of Qatar. Circ Econ Sust. https://doi.org/10.1007/s43615-021-00037-w
16. World Bank (2018) Beyond scarcity: water security in the Middle East and North Africa; MENA development series. World Bank, Washington, DC
17. United Nations World Water Assessment Programme (2017) Wastewater: the untapped resource. In: The United Nations World Water Development Report 2017; UNESCO: Paris, France

18. Morris JC, Georgiou I, Guenther E, Caucci S (2021) Barriers in implementation of wastewater reuse: identifying the way forward in closing the loop. Circ Econ Sust 1:413–433. https://doi.org/10.1007/s43615-021-00018-z
19. Stefanakis AI, Akratos CS, Tsihrintzis VA (2014) Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment. Elsevier Publishing, Amsterdam
20. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
21. Stefanakis AI (2018) Constructed wetlands for industrial wastewater treatment, 1st edn. Wiley, Chichester
22. Tatoulis T, Stefanakis AI, Frontistis Z, Akratos CS, Tekerlekopoulou AG, Mantzavinos D, Vayenas DV (2017a) Treatment of table olive washing water using trickling filters, constructed wetlands and electrooxidation. Environ Sci Pollut Res:1–8. https://doi.org/10.1007/s11356-016-7058-6
23. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
24. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2020) Treatment of cork boiling wastewater using a horizontal subsurface flow constructed wetland combined with ozonation. Chemosphere 260:127598
25. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
26. Stefanakis AI, Seeger E, Dorer C, Sinke A, Thullner M (2016) Performance of pilot-scale horizontal subsurface flow constructed wetlands treating groundwater contaminated with phenols and petroleum derivatives. Ecol Eng 95:514–526
27. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
28. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10:127. https://doi.org/10.3390/app10010127
29. Gholipour A, Zahabi H, Stefanakis AI (2020) A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. Chemosphere 247:125966
30. Tatoulis T, Akratos CS, Tekerlekopoulou AG, Vayenas DV, Stefanakis AI (2017) A novel horizontal subsurface flow constructed wetland: reducing area requirements and clogging risk. Chemosphere 186:257–268
31. Molle P, Lienard A, Boutin C, Merlin G, Iwema A (2005) How to treat raw sewage with constructed wetlands: an overview of the French systems. Water Sci Technol. https://doi.org/10.2166/wst.2005.0277
32. Al Sulaimi A, Barghash H, Stefanakis AI (2017) A demo constructed wetland for domestic wastewater treatment at the EcoHaus of the German University of Technology in Oman. In Proceedings of the world water day event. German University of Technology in Oman, Halban
33. Knebel N (2019) Crossing the borders between teaching, research and practice: a university project for a zero-energy building in Oman. KnE Soc Sci 2019:389–402
34. Stefanakis AI, Tsihrintzis VA (2012) Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands. Chem Eng 181–182:416–430
35. Nivala J, Abdallat G, Aubron T, Al-Zreiqat I, Abbassi B, Wu GM, van Afferden M, Müller RA (2019) Vertical flow constructed wetlands for decentralized wastewater treatment in Jordan: optimization of total nitrogen removal. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2019.03.376
36. Pan J, Zhang H, Li W, Ke F (2012) Full-scale experiment on domestic wastewater treatment by combining artificial aeration vertical- and horizontal-flow constructed wetlands system. Water Air Soil Pollut. https://doi.org/10.1007/s11270-012-1306-2

37. Saeed T, Miah MJ, Majed N, Alam MK, Khan T (2021) Effect of effluent recirculation on nutrients and organics removal performance of hybrid constructed wetlands: landfill leachate treatment. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.125427
38. Arias CA, Brix H, Marti E (2005) Recycling of treated effluents enhances removal of total nitrogen in vertical flow constructed wetlands. J Environ Sci Health Part A Toxic/Hazard Substan Environ Eng. https://doi.org/10.1081/ESE-200055882
39. Stefanakis AI, Akratos CS, Tsihrintzis VA (2011) Effect of wastewater step-feeding on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecol Eng 37(3):431–443
40. Li F, Lu L, Zheng X, Ngo HH, Liang S, Guo W, Zhang X (2014) Enhanced nitrogen removal in constructed wetlands: effects of dissolved oxygen and step-feeding. Bioresour Technol. https://doi.org/10.1016/j.biortech.2014.07.004
41. Wang Y, Shen L, Wu J, Zhong F, Cheng S (2020) Step-feeding ratios affect nitrogen removal and related microbial communities in multi-stage vertical flow constructed wetlands. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.137689
42. Wu S, Kuschk P, Brix H, Vymazal J, Dong R (2014) Development of constructed wetlands in performance intensifications for wastewater treatment: a nitrogen and organic matter targeted review. Water Res. https://doi.org/10.1016/j.watres.2014.03.020
43. Alwahaibi B, Jafary T, Al-Mamun A, Baawain MS, Aghbashio M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. https://doi.org/10.1016/j.jclepro.2021.126558
44. Jaffar AKS, Ahmed M, Al-Wardy M, Al-Busaidi A, Choudri BS (2017) Wastewater and sludge management and research in Oman: an overview. J Air Waste Manag Assoc. https://doi.org/10.1080/10962247.2016.1243595
45. Stefanakis AI, Bardiau M, Silva D, Taylor H (2019) Presence of bacteria and bacteriophages in full-scale trickling filters and an aerated constructed wetland. Sci Total Environ 659:1135–1145
46. Wallace S, van Oirschot D, Stefanakis AI (2019) Aerated wetlands. In: Langergraber G, Dotro G, Nivala J, Rizzo A, Stein OR (eds) Wetland technology—practical information on the design and application of treatment wetlands, 1st ed.; scientific and technical report series no. 27. International Water Association Publishing, London, UK, pp 105–107
47. Nivala J, Murphy C, Freeman A (2020) Recent advances in the application, design, and operations & maintenance of aerated treatment wetlands. Water 12:1188
48. Stefanakis AI (2020) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 503–525
49. Stefanakis AI, Prigent S (2018) A novel two-stage constructed wetland with integrated sludge management and artificial aeration to meet strict effluent quality standards. In Proceedings of the 16th IWA international conference on wetland systems for water pollution control, Valencia, Spain, 30 Sept–10 Oct
50. Saeed T, Sun GZ (2011) Enhanced denitrification and organics removal in hybrid wetland columns: comparative experiments. Bioresour Technol 102:967–974
51. Fan J, Liang S, Zhang B, Zhang J (2013) Enhanced organics and nitrogen removal in batch operated vertical flow constructed wetlands by combination of intermittent aeration and step feeding strategy. Environ Sci Pollut Res 20:2448–2455
52. Aditya R (2016) Produced water treatment market by application (onshore & offshore), by treatment types (physical, chemical, membrane and others), & by geography. Global Trends & Forecast to 2019
53. Jain P, Sharma M, Dureja P, Sarma PM, Lal B (2017) Bioelectrochemical approaches for removal of sulfate, hydrocarbon and salinity from produced water. Chemosphere 166:96–108
54. Kim KH, Jahan SA, Kabir E, Brown RJ (2013) A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. Environ Int 60:71–80

55. Arthur J, Langhus B, Patel C (2005) Technical summary of oil & gas produced water treatment technologies. Tulsa, Oklahoma, pp 1–53
56. Munirasu S, Haija MA, Banat F (2016) Use of membrane technology for oil field and refinery produced water treatment – a review. Proc Saf Environ 100:183–202
57. Igunnu ET, Chen GZ (2013) Produced water treatment technologies. Int J Low Carbon Tech 9:157–177
58. An C, Huang G, Yao Y, Zhao S (2017) Emerging usage of electrocoagulation technology for oil removal from wastewater: a review. Sci Total Environ 579:537–556
59. Daee M, Gholipour A, Stefanakis AI (2019) Performance of pilot horizontal roughing filter as polishing stage of waste stabilization ponds in developing regions and modelling verification. Ecol Eng 138:8–18
60. Stefanakis AI, Thullner M (2016) Fate of phenolic compounds in constructed wetlands treating contaminated water. In: Ansari AA, Gill SS, Gill R, Lanza G, Newman L (eds) Phytoremediation, vol 4. Springer International Publishing, Switzerland, pp 311–325
61. Mozaffari MH, Shafiepour E, Mirbagheri SA, Rakhshandehroo G, Wallace S, Stefanakis AI (2021) Hydraulic characterization and removal of metals and nutrients in an aerated horizontal subsurface flow "racetrack" wetland treating primary-treated oil industry effluent. Water Res 200:117220
62. Knight RL, Robert H, Kadlec H, Ohlendorf M (1999) The use of treatment wetlands for petroleum industry effluents. Environ Sci Technol 33(7):973–980
63. Wallace S, Schmidt M, Larson E (2011) Long term hydrocarbon removal using treatment wetlands. SPE annual technical conference and exhibition, Denver, Colorado, USA, 30 Oct–2 Nov
64. Saad ASG, Khadam MA, Agab MA (2009) Biological method for treatment of petroleum water oil content in Sudan. University of Khartoum. Available at http://research.uofk.edu/multisites/UofK_research/images/stories/research/PDF/BESBC/biological%20treatment.pdf
65. Ji GD, Sun TH, Ni JR (2007) Surface flow constructed wetland for heavy oil-produced water treatment. Bioresour Technol 98:436–441
66. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, pp 25–42
67. Stefanakis AI (2021) Promoting sustainability in the oil industry: the benefits of using constructed wetlands for oily wastewater treatment. In: Davis C, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. International Water Association – IWA Publishing, London UK, pp 423–430
68. Abed RMM, Al-Kharusi S, Prigent S, Headley T (2014) Diversity, distribution and hydrocarbon biodegradation capabilities of microbial communities in oil-contaminated cyanobacterial mats from a constructed wetland. PLoS One 9(12):e114570
69. Breuer R, Grissemann E (2011) Produced water treatment using wetlands-Reducing the environmental impact of oilfield operations, Paper presented at the SPE European Health, Safety and Environmental Conference in Oil and Gas Exploration and Production, Vienna, Austria, Paper Number: SPE-140124-MS. https://doi.org/10.2118/140124-MS
70. Stefanakis AI (2021) A circular model for sustainable produced water management in the oil and gas industry. In: Stefanakis AI, Nikolaou I (eds) Circular economy and sustainability, vol volume II. Elsevier Publishing, Amsterdam, Netherlands
71. Echchelh A, Hess T, Sakrabani R, Prigent S, Stefanakis AI (2021) Towards agro-environmentally sustainable irrigation with treated produced water in hyper-arid environments. Agric Water Manag 243:106449
72. Stefanakis AI, Al-Hadrami A, Prigent S (2017) Reuse of oilfield produced water treated in a constructed wetland for saline irrigation under desert climate. 7th international symposium on wetland pollutant dynamics and control – WETPOL, Montana, USA, 21–25 Aug 2017

73. Stefanakis AI, Charalampopoulos I, Psomiadis E, Prigent S (2018) The thermal regime of a large constructed wetland in the desert environment. 16th IWA international conference on wetland systems for water pollution control, Valencia, Spain, Sept 30–Oct 1
74. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Piro P, Palermo SA, Turco M, Pirouz B, Stefanakis A, Regelsberger M, Ursino N, Carvalho PN (2021) Management of urban waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334

Chapter 13
Constructed Wetlands for Sustainable Wastewater Treatment – Case Studies from Pakistan

Atif Mustafa and Muhammad Afzal

Abstract Like other countries across the globe, Pakistan's fresh water resources are stressed by increasing water demand, environmental degradation and the multi-faceted impacts of climate change. Most of the wastewater generated by urban, industrial and agricultural activities is discharged untreated into water bodies thus polluting the vulnerable water resources. The contemporary wastewater treatment systems in most of the developing countries including Pakistan fail to treat wastewater satisfactorily. Reasons for poor treatment include lack of local expertise, high maintenance costs and poor governance. These wastewater treatment systems also require heavy capital investment and high operating and energy costs. Over the years, responsible water management departments in different parts of the world have started diverting to nature-based solutions to mitigate the severe climatic, environmental, economic and societal challenges. Nature-based approaches including constructed wetlands represent more efficient and cost-effective solutions than traditional methods as they are self-operating and self-maintaining. Constructed wetlands (CWs) are passive treatment systems and temperature has a profound impact on the efficiency of CWs; low temperatures reduce the biological activity and decrease the rate of chemical reactions that are important pathways for contaminant transformation and their subsequent removal. CWs have been widely implemented in the developed world where thousands of systems are currently working. These systems are mostly located in geographical locations where temperatures are considerably low. Most of the developing countries including Pakistan are located in regions where temperatures are considerably high and may have arid conditions. This chapter discusses case studies from Pakistan where different types of CW

A. Mustafa (✉)
Department of Environmental Engineering, NED University of Engineering and Technology, Karachi, Pakistan
e-mail: atifm@neduet.edu.pk

M. Afzal
Soil and Environmental Biotechnology Division, National Institute for Biotechnology and Genetic Engineering (NIBGE), Faisalabad, Pakistan
e-mail: afzal@nibge.org

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_13

systems have been tested in hot and arid climatic locations. The role of plant-associated microorganisms in the removal of pollutants in CWs is also highlighted. The various aspects of different variants of CWs including free water surface, horizontal flow, vertical flow and floating CWs treating domestic, textile, and produced water from oil and gas field are discussed in this chapter.

Keywords Constructed wetlands · Wastewater treatment · Developing countries · Nature-based · Vertical flow · Horizontal flow · Free water surface · Floating wetlands · Pakistan

13.1 Background

Most of the arid and semi-arid regions are located in developing countries where freshwater availability is continuously decreasing. Pakistan has an arid to semiarid climate with variability in temperature [1]. The countries face challenges of both water scarcity and water quality degradation. Rapid industrialization and urbanization have enhanced environmental deterioration by the release of different types of organic and inorganic chemicals in the environment. Among the different types of waste from industries and urban population, wastewater is considered one of the main sources of water pollution. Domestic and industrial wastewater contains oil and grease, detergents, dyes, drug residues, heavy metals, and pathogenic microbes that pollute the water bodies. Most of these chemicals are toxic and cause mutagenic and carcinogenic effects on living organisms [2, 3].

In Pakistan, most of the domestic and industrial wastewater is discharged into the environment with little or no treatment. In case of sewage treatment, centralized treatment plants are present in cities like Karachi and Islamabad but are not operating efficiently. While in case of industries only a few large industrial units have installed conventional wastewater treatment plants. The lower number of wastewater treatment facilities installation at industries is due to very high capital, operational, and maintenance costs [2, 4]. Most of the small and medium enterprises (SMEs) are incapable of applying and operating conventional wastewater treatment technologies, since these are expensive and technically not feasible and applicable in developing countries like Pakistan [5]. Due to these facts, most of the domestic and industrial wastewater in developing countries including Pakistan is discharged into the environment without any treatment.

The use of constructed wetlands (CWs), and in particular floating constructed wetlands (FCWs), is an applicable, feasible, and sustainable approach in developing countries for the remediation of sewage and industrial wastewater [6–9, 10]. Their low cost and self-sustainability make them a feasible approach in developing countries for the treatment and reuse of wastewater. The use of FCWs is highly recommended for the removal of contaminants from water in the developing countries due to its low application and maintenance costs [11]. In these CWs, the plants and their associated microorganisms are involved in the removal of contaminants from the water [12–14]. However, one of the main limitations of CWs is that some of the contaminants are toxic to both plants and their associated microbial population, ultimately reducing plant development and contaminants removal efficiency [15]. To overcome this limitation, the augmentation of CWs and FCWs with specific bacteria possessing plant-growth-promoting and pollutants-degrading capabilities is recommended [16–18]. In this synergy, plants provide space for the colonization of the bacteria and nutrients for their growth. In return, bacteria improve plant growth by providing plant growth-promoting enzymes and nutrients and detoxifying the water by mineralizing the contaminants.

Generally, Pakistan has a warm climate; hence it is suitable for the application of CWs for wastewater remediation. It is well known that high temperatures have a positive impact on CWs performance [19]. The average annual temperature is within the range of 16–27 °C and exceeds 30 °C during summer months, thus providing optimal conditions for many biological processes and biological activity by microorganisms [20]. Many wetland plants, such as *Typha domingensis*, *Phragmites australis*, *Cyperus laevigatus*, and *Cana indica* are abundantly found in the wastewater drains and ponds, water lakes, and the banks of canals. The bacterial strains isolated from these plants have shown the potential to degrade different types of organic pollutants and exhibited plant growth-promoting activities [14, 17]. The combined use of these plants and their associated bacteria has been found a more efficient approach for the remediation of sewage and industrial wastewater than the use of only plants in CWs and FCWs [15, 16, 22].

In Pakistan, both CWs and FCWs have been successfully applied in the field for the wastewater remediation [16–18, 21, 23–25]. These wetlands have shown the potential to remediate both domestic as well as industrial wastewaters. In this chapter, the use of selected CWs including FCWs (Table 13.1) in Pakistan has been discussed. Moreover, the indigenous wetland plants and their pollutant degradation efficiency are also discussed. The potential of plant-bacteria synergy to enhance the wastewater treatment efficacy of CWs has also been explained.

Table 13.1 Types of constructed wetlands applied in different hot areas of Pakistan

No.	Location	Constructed wetland type	Wastewater type	Maximum summer temperature (°C)
1	Chakwal	Floating	Industrial	40
2	Faisalabad	Floating, vertical	Industrial	40
3	Kamber-Shahdadkot	Surface flow	Industrial	>50
4	Karachi	Surface flow	Domestic	40
5	Manora island	Subsurface flow	Domestic	40

13.2 Domestic Wastewater Treatment

This section gives insight into projects that have used CW for sewage treatment in Pakistan. The CW technology has been used in Karachi, the largest city of the country. The Köppen-Geiger climate classification system categorizes the city's climate as BWh, which indicates a hot desert climate. The average annual temperature is 25.9 °C while maximum summer temperature can reach up to 40 °C; precipitation is approximately 194 mm (7.6 inches) per year.

A CW treatment system was commissioned at NED University of Engineering & Technology, Karachi that has coordinates of longitude 25° 56′8″ N and latitude 67° 06′ 44″ E. This pilot-scale system is designed as horizontal surface flow (HSF) CW to treat primary wastewater effluent (Fig. 13.1). The HSF CW was selected as this type of system does not have problem of clogging. The CW is designed as a plug flow reactor and the length to width ratio (L: W) is 4:1. The cell design consists of a rectangular bed, bordered with masonry work of 0.25 m wall and concrete based floor to protect seepage of wastewater. The system is designed for a flow of 1 m^3/d and is planted with common reed plant (*Phragmites*). Pre-treated wastewater from a conventional activated sludge plant is collected and fed to a storage tank placed at the influent end of the wetland; the influent entering the CW is controlled manually by adjusting the valve attached to the inlet pipe. Figure 13.1 shows the layout of the CW that is added to the treatment train. The pre-treated wastewater has the following quality: 5-day Biochemical Oxygen Demand ($BOD_{5)}$) 32.5–110 mg/L, Chemical Oxygen Demand (COD) 56–225 mg/L, Total Suspended Solids (TSS) 95–350 mg/L,

Fig. 13.1 A pilot-scale horizontal surface flow constructed wetland in Karachi for effluent reuse (**a**) during plant establishment period (**b**) after establishment period. (Photo courtesy A. Mustafa)

Ammonia Nitrogen (NH_4-N) 10–29 mg/L, Ortho-Phosphate (PO_4-P) 4.5–10.2 mg/L, Total Coliforms and Faecal Coliforms 2.1 × 10^6 counts/100 mL and 1.1 × 10^6 counts/100 mL, respectively. The wastewater passes through the horizontal surface flow wetland and is then collected for potential irrigation reuse.

The average reduction in BOD and COD concentrations was close to 50%. The variability in influent BOD and COD concentration was due to intermittent power failure resulting from power outage. However, the CW performance shows that the system has a good buffer capacity and is able to endure organic shock loads. There was a decrease in the inlet and outlet BOD_5/COD ratio from 0.55 to 0.27 showing that organic matter susceptible to biological degradation was degraded by the CW system. About 48% of the effluent BOD concentrations were below the threshold of 30 mg/L as set by US EPA for wastewater reuse, after the start-up months. Average solids removal efficiency was 78%. About 38% of effluent SS concentrations were below the threshold of 30 mg/L as set by US EPA for wastewater reuse, again with the exception of the first start-up months. The reduction in ammonia-nitrogen concentration for this study was 49%. The CW reduced both total and faecal coliforms at the average range of 93–99%, showing a high efficiency in removing the pathogens [23].

Another CW system for sewage treatment has been commissioned at Manora Island in the vicinity of Karachi (Fig. 13.2). The purpose of this subsurface flow CW system is to treat approximately 120 m^3/day of sewage and reuse it. The reclaimed water has reduced water resource for irrigation of sports field covering an area of 1.21 hectares and sustaining green belts and tree plantations in the island. The treatment system comprises of screening, grit chamber, baffled setting tanks and finally CWs. It is an economical treatment system as it utilizes energy only for the initial pumping and thereafter uses a natural gradient for wastewater to flow through the various treatment units. The subsurface flow system comprises a total area of 325 m^2

Fig. 13.2 A full-scale subsurface flow CW at Manora island in the vicinity of Karachi for effluent reuse (**a**) during plant establishment period, and (**b**) after the establishment period (Mangroves for the Future, MFF)

divided into three equal beds. All beds are planted with *Canna Indica* species and have an aspect ratio of L:W equal to 1.5:1. The inflow sewage has characteristics equivalent to that of medium strength domestic wastewater, while the effluent of the system meets the international reuse standards [26].

Another interesting project is retrofitting of a pond system treating sewage to a floating CW in Karachi. The pond receives domestic wastewater and has a treatment capacity of approximately 50 m^3/d. The total surface area of the pond system is 242 m^2 and more than 20% of the pond surface area was covered with FCW (Fig. 13.3). Insulation sheets of 50 mm thickness made of PE material and dimensions of 1.8 m × 1.2 m were used as a base material for the FCW. Three different emergent plant species (*Typha*, *Canna:* red, green, yellow, and *Cypreus Papyrus*) were planted in the sheet holes that were filled with sand and fertilizer. The FCW not only improved the water quality but has also improved the aesthetic quality and supported biodiversity. Various bird species, butterflies and dragon flies are noticed now in the area.

The average effluent TSS, BOD and COD concentrations from the pond system without the FCW were 75.3 mg/L, 85 mg/L and 195 mg/L, respectively. However, after pond retrofitting with FCW, the effluent TSS, BOD and COD concentrations were reduced to 25 mg/L, 25 mg/L, and 58 mg/L respectively. Nutrients and pathogens removal also improved as a result of the addition of the FCW to the pond system. The removal efficiency for the monitored water quality parameters TSS, BOD, COD, NH_4-N, PO_4-P increased by 34%, 25.7%, 42%, 51.5%, and 27.6% respectively. This study showed that floating CWs can be applied as a sustainable and zero-energy technology for retrofitting the existing pond treatment systems.

Fig. 13.3 A floating CW for retrofitting a pond system treating sewage in Karachi, Pakistan. (Photo courtesy A. Mustafa)

13.3 Industrial Wastewater Treatment

This section provides insights into projects that have used CWs for industrial wastewater treatment in Pakistan. A floating CW was used in a wastewater pit of an oil exploration company for the remediation of crude oil contaminated wastewater (Fig. 13.4). The system is located in the district Chakwal of Pakistan (33°01′30.4″N 73°09′18.3″E). The area has high summer temperatures that reach up to 40 °C.

The floating mat has an area of 3058 m^2 and was planted with *Phragmites australis, Typha domingensis, Leptochloa fusca,* and *Brachiaria mutica*. The treatment system was inoculated with a consortium of 10 different alkane-degrading bacteria. The bacterial strains were *Ochrobactrum intermedium* R2, *Microbacterium oryzae* R4, *Pseudomonas aeruginosa* R25, *P. aeruginosa* R21 (isolated from crude oil-contaminated soil), *Acinetobacter* sp. LCRH81, *Klebsiella* sp. LCRI-87 (isolated from the rhizosphere and root interior of *Lecucaena leucocephala*, respectively), *Acinetobacter* sp. BRSI56, *P. aeruginosa* BRRI54 (isolated from the shoot and root interior of *Brachiaria mutica*, respectively), *Bacillus subtilus* LORI66 (isolated from the root interior of *Lolium perenne*), and *Acinetobacter junii* TYRH47 (isolated from the rhizosphere of *T. domingensis*). These strains have the ability to degrade hydrocarbons, produce biosurfactants and promote plant growth.

The crude oil contaminated wastewater had high levels of contaminants: COD (1316 mg /L), BOD_5 (365 mg /L), hydrocarbon content (319 mg/L), TDS (8050 mg/L), chlorides (1330 mg/L), Cd (0.98 mg/L), and Pb (0.62 mg/L). Monitoring of the water samples showed good removal efficiencies for COD (97.4%), BOD (98.9%), TDS (82.4%), hydrocarbon content (99.1%), and heavy metals (80%), within 18 months [25]. All the FCW plants grew well: maximum growth (biomass and length of roots and shoots) was exhibited for *P. australis*. The inoculated bacteria showed persistence in the water, rhizoplane, roots, and shoots of the plants of FCWs. This project demonstrated that FCWs can be applied for the remediation of crude oil-contaminated wastewater.

Another interesting project is treatment of produced water by a pilot-scale wetland system established at a gas field located in the Sindh province of Pakistan. This wetland system was commissioned in 2013. The gas field is located in a warm

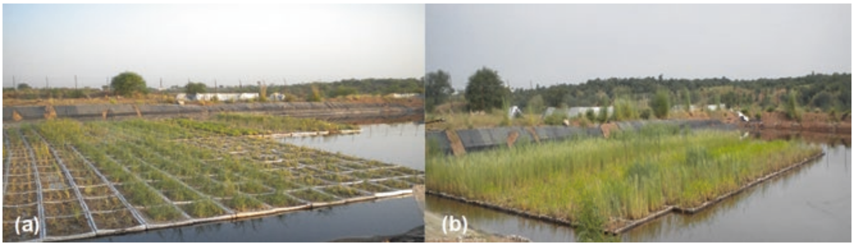


Fig. 13.4 Application of floating treatment wetlands for treatment of crude oil-contaminated wastewater in Chakwal, Pakistan: (**a**) the system after plantation, and (**b**) after 6 months. (Photo courtesy M. Afzal)

climate region where summer temperatures exceed 50 °C and has very scanty rainfall. The purpose of this project was to test the feasibility of full-scale CWs for treating produced water containing petroleum hydrocarbons under the local environmental conditions. The system was a Free Water Surface (FWS) CW with two cells covering an overall area of 100 m^2 (Fig. 13.5). The first cell was planted with *Phragmites* while the second cell with *Typha.* Design modification included provision of additional berms composed of gravel in the wetland cells. The system was fed with 3 m^3/day of produced water and an operating water depth of 45 cm was maintained.

The average influent concentrations of benzene, toluene, ethyl benzene and xylene were 1.57 mg/L, 0.14 mg/L, 0.29 mg/L and 2.14 mg/L, respectively [27]. The wetland system removed the BTEX compounds and the removal efficiencies were benzene (93%), toluene (93%), ethyl benzene (98%) and xylene (89.4%). Stefanakis, A.I., 2020 reports that a CW system commissioned at the Nimr oilfield in Oman (hot and arid climate) is one of the largest CW system that successfully treats produced water generated by the oilfield [28, 29, 30]. Metagenomic analyses of the bacterial community retrieved from the wetland system commissioned in the Sindh province of Pakistan showed majority of sequences were related to phyla *proteobacteria*. Sequencing of 16S rDNA amplicons followed by bioinformatics analysis illustrated that the CW sheltered a high diversity of microbes as shown by the richness of operational taxonomic units.

A CW was developed in the vicinity of a textile industry located in Faisalabad (31° 29′N, 73° 17′E) for the remediation of dye-rich wastewater [16–18]. The Köppen-Geiger climate classification system categorizes the city's climate as BWh (hot desert climate). In summer, the temperatures are as high as 41 °C. The operational process of CWs was optimized for the remediation of dye-rich textile wastewater [13, 16] before its application in the industry. In the first phase, horizontal flow CWs planted with *L. fusca* and inoculated with endophytic bacteria possessing dyes-degrading potential were tested [16]. The horizontal flow CWs efficiently removed dyes and other pollutants from the wastewater and their potential to remediate the wastewater was further enhanced by the inoculation of bacteria in the

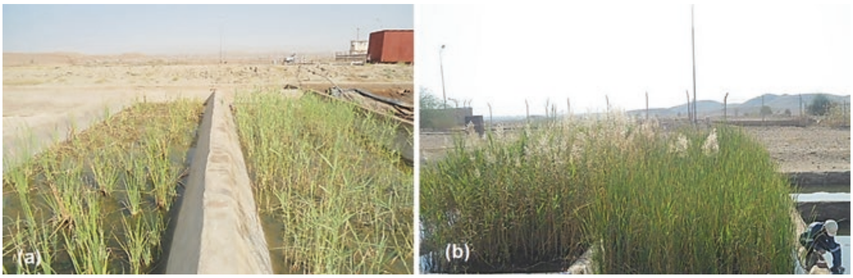


Fig. 13.5 A free water surface CW for the treatment of produced water in Sindh province of Pakistan: (**a**) during the plant establishment period (**b**) during the operational period. (Photo courtesy Z. Raza)

CWs. After 48 hours, COD and BOD were reduced from 493 to 70 mg/L (86%) and 190 to 42 mg/L (78%), respectively. Toxicity test revealed that treated wastewater was non-toxic, and the endophytes showed persistence in the water, rhizoplane, root and shoot.

In the second phase, CWs were developed in the vicinity of a textile industry. Vertical flow CWs planted with *Brachiaria mutica* and inoculated with endophytic bacteria were used for the remediation of dye-rich wastewater. The vertical flow CWs efficiently removed the dye and other pollutants from the wastewater and their performance was enhanced by the bacterial application. Similarly, bleaching wastewater of the industry was treated in bacterial augmented pilot-scale horizontal flow CWs vegetated with *L. fusca* [17]. The CWs removed the organic and inorganic pollutants from the wastewater, and maximum COD (86%), and BOD (78%) removal was observed in the bacterial augmented wetlands. FCWs were also applied in the industry for the remediation of dye-rich wastewater [18]. The FCWs were developed by the vegetation of *P. australis* and inoculated with dye-degrading bacteria (Fig. 13.6). This modified version of CWs also efficiently removed dyes and other organic and inorganic pollutants from the textile wastewater. It reduced the COD (92%), BOD (91%), color (86%), and heavy metals (87%) from the inflow wastewater thus producing effluents that met the local wastewater discharge standards.

Very recently, hybrid wetland systems including FCWs have been designed and commissioned at two Toyota car-wash centers in Faisalabad for the treatment and reuse of their wastewater. Similarly, FCWs have recently been used to treat beverage industry wastewater in Islamabad, Pakistan.

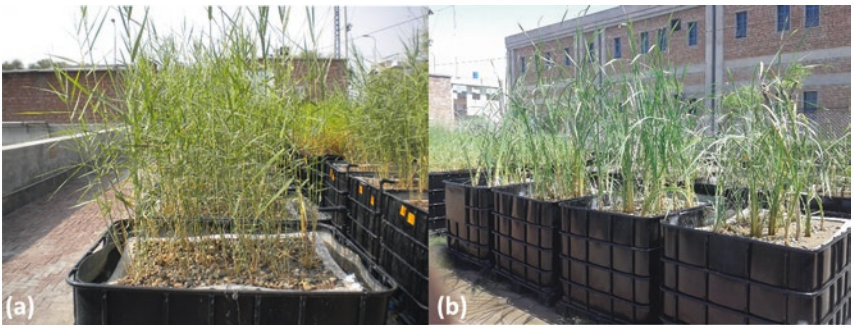


Fig. 13.6 Floating treatment wetlands inoculated with dye-degrading bacteria in the vicinity of the textile industry located in Faisalabad, Pakistan for the remediation of dye-rich textile wastewater planted with (**a**) *Phragmites australis* and (**b**) *Typha domingensis*. (Photo courtesy M. Afzal)

13.4 Conclusions

Water scarcity is one of the main global challenges and needs to be addressed in a sustainable manner. One of the possible ways to overcome this problem is treatment of wastewater and its reuse for the same application or irrigation, or at least its safe disposal to the environment. Constructed wetlands are a low-cost and sustainable approach for the treatment and reuse of wastewater in developing countries that have arid and hot climatic conditions. This green technology has been successfully applied in Pakistan for the remediation of sewage and various types of industrial wastewater. It is anticipated that the application of constructed wetlands for the remediation and reuse of wastewater in Pakistan will increase with time providing added benefits of energy conservation, enhanced biodiversity and sustainability.

References

1. Chaudhary QZ, Rasul G (2004) Agro-climatic classification of Pakistan. Sci Vis 9:59–66
2. Nabi G, Ali M, Khan S, Kumar S (2019) The crisis of water shortage and pollution in Pakistan: risk to public health, biodiversity, and ecosystem. Environ Sci Pollut Res 26:10443–10445
3. Martinez-Guerra E, Ghimire U, Nandimandalam H, Norris A, Gude VG (2020) Wetlands for environmental protection. Water Environ Res 92:1677–1694
4. Jabeen A, Huang X, Aamir M (2015) The challenges of water pollution, threat to public health, flaws of water Laws and Policies in Pakistan. J Water Resource Protect 7:1516–1526
5. Shahid MJ, Tahseen R, Siddique M, Ali S, Iqbal S, Afzal M (2019) Remediation of polluted river water by floating treatment wetlands. Water Supply 19:967–977
6. Chen Z, Cuervo DP, Muller JA, Wiessner A, Koser H, Vymazal J et al (2016) Hydroponic root mats for wastewater treatment-a review. Environ Sci Pollut Res Int 23:15911–15928
7. Alvarez JA, Avila C, Otter P, Kilian R, Istenic D, Rolletschek M et al (2017) Constructed wetlands and solar-driven disinfection technologies for sustainable wastewater treatment and reclamation in rural India: SWINGS project. Water Sci Technol 76:1474–1489
8. Colares GS, Dell'Osbel N, Wiesel PG, Oliveira GA, Lemos PHZ, da Silva FP (2020) Floating treatment wetlands: a review and bibliometric analysis. Sci Total Environ 714:136776
9. Jia L, Liu H, Kong Q, Li M, Wu S, Wu H (2020) Interactions of high-rate nitrate reduction and heavy metal mitigation in iron-carbon-based constructed wetlands for purifying contaminated groundwater. Water Res 169:115285
10. Gaballah MS, Ismail K, Aboagye D, Ismail MM, Sobhi M, Stefanakis AI (2021) Effect of design and operational parameters on nutrients and heavy metal removal in pilot floating treatment wetlands with Eichhornia Crassipes treating polluted lake water. Environ Sci Pollut Res 28(20):25664–25678. https://doi.org/10.1007/s11356-021-12442-7
11. Masi F, Rizzo A, Regelsberger M (2018) The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. J Environ Manag 216:275–284
12. Sleytr K, Tietz A, Langergraber G, Haberl R, Sessitsch A (2009) Diversity of abundant bacteria in subsurface vertical flow constructed wetlands. Ecol Eng 35:1021–1025
13. Shehzadi M, Afzal M, Islam E, Mobin A, Anwar S, Khan QM (2014) Enhanced degradation of textile effluent in constructed wetland system using *Typha domingensis* and textile effluent-degrading endophytic bacteria. Water Res 58:152–159
14. Shehzadi M, Fatima K, Imran A, Mirza M, Khan Q, Afzal M (2016) Ecology of bacterial endophytes associated with wetland plants growing in textile effluent for pollutant-degradation and plant growth-promotion potentials. Plant Biosys 150:1261–1270

15. Rehman K, Imran A, Amin I, Afzal M (2018) Inoculation with bacteria in floating treatment wetlands positively modulates the phytoremediation of oil field wastewater. J Hazard Mater 349:242–251
16. Hussain Z, Arslan M, Malik MH, Mohsin M, Iqbal S, Afzal M (2018) Treatment of the textile industry effluent in a pilot-scale vertical flow constructed wetland system augmented with bacterial endophytes. Sci Total Environ 645:966–973
17. Hussain Z, Arslan M, Shabir G, Malik MH, Mohsin M, Iqbal S et al (2019) Remediation of textile bleaching effluent by bacterial augmented horizontal flow and vertical flow constructed wetlands: a comparison at pilot scale. Sci Total Environ 685:370–379
18. Tara N, Arslan M, Hussain Z, Iqbal M, Khan QM, Afzal M (2019) On-site performance of floating treatment wetland macrocosms augmented with dye-degrading bacteria for the remediation of textile industry wastewater. J Clean Prod 217:541–548
19. Paing J, Guilbert A, Gagnon V, Chazarenc F (2015) Effect of climate, wastewater composition, loading rates, system age and design on performances of French vertical flow constructed wetlands: a survey based on 169 full scale systems. Ecol Eng 80:46–52
20. Metcalf & Eddy (2014) Wastewater engineering: treatment and resource recovery. McGraw-Hill Higher Education, New York
21. Hashmat AJ, Afzal M, Fatima K, Anwar-ul-Haq M, Khan QM, Arias CA et al (2019) Characterization of hydrocarbon-degrading bacteria in constructed wetland microcosms used to treat crude oil polluted water. Bull Environ Contam Toxicol 102:358–364
22. Ijaz A, Shabir G, Khan QM, Afzal M (2015) Enhanced remediation of sewage effluent by endophyte-assisted floating treatment wetlands. Ecol Eng 84:58–66
23. Mustafa A (2013) Constructed wetland for wastewater treatment and reuse: a case study of developing country. Int Jou Env Sci Dev 4:20–24
24. Afzal M, Arslan M, Müller JA, Shabir G, Islam E, Tahseen R (2019) Floating treatment wetlands as a suitable option for large-scale wastewater treatment. Nat Sustain 2:863–871
25. Afzal M, Rehman K, Shabir G, Tahseen R, Ijaz A, Hashmat AJ (2019) Large-scale remediation of oil-contaminated water using floating treatment wetlands. NPJ Cln Wat 2:3
26. http://www.mangrovesforthefuture.org/grants/medium-grant-facilities/pakistan/demonstration-of-wastewater-treatment-for-reduction-of-coastal-water-contamination-from-manora-island-karachi/
27. Mustafa A, Azim MK, Raza Z, Kori JA (2018) BTEX removal in a modified free water surface wetland. Chem Eng J 333:451–455
28. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12:1665
29. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10(1):127. https://doi.org/10.3390/app10010127
30. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert wetlands for industrial wastewater treatment. John Wiley & Sons Ltd, Chichester, UK, pp 25–42. https://doi.org/10.1002/9781119268376.ch1

Chapter 14
Constructed Wetland Case Studies for Municipal and Glass Industry Wastewater Treatment in Iran

Amir Gholipour and Alexandros Stefanakis

Abstract The use of conventional/mechanical methods for wastewater treatment is not always economically and technically feasible in low-income regions and small/medium rural or remote communities. Thus, the use of nature-based solutions such as constructed wetlands (CW) is viewed as an attractive and feasible alternative. However, the application of CW in the Middle East region is limited; in particular in Iran, CW technology remains largely unknown with very few and scattered applications. Therefore, this chapter presents two CW case studies from Iran. The first is a unique application of a CW system for wastewater treatment from a glass manufacturing industry, while the second is a hybrid CW treating wastewater from a University dormitory. Both CW systems are full-scale facilities and are already in operation. Such case studies demonstrate not only the technical efficiency of this sustainable technology, but also its potential to provide a solution under arid and warm climates.

Keywords Constructed wetlands · Nature-based solutions · Arid climate · Glass industry · University dormitory · Greywater · Reuse · Recycling · Irrigation · Iran

A. Gholipour (✉)
LEAF – Linking Landscape, Environment, Agriculture and Food, Institute Superior de Agronomia (ISA), University of Lisbon, Tapada da Ajuda, Lisbon, Portugal
e-mail: amirgholipour@isa.ulisboa.pt

A. Stefanakis
Laboratory of Environmental Engineering and Management, School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece

EURECA-PRO – The European University on Responsible Consumption and Production, Chania, Greece
e-mail: astefanakis@tuc.gr

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_14

14.1 Introduction

Despite the fact that wastewater treatment and utilization are crucial in terms sanitation services and economic benefits, wastewater recycling plays an important role in tackling water scarcity and it brings several economic and environmental advantages [1, 2]. This is particularly important in water scarce areas such as the Middle East with regions of zero to minimum average precipitation [3]. However, the Middle Eastern climatic conditions vary greatly, depending on the season and the geography. The basic climate of the Middle East can be characterized as hot and dry, with winters being mild with some rain [4]. The exception is the mountainous areas, where desert turns to steppe in northern Iraq, northern Iran and eastern Turkey. Regarding Iran's climate, it hot and dry with long, hot, dry summers and short, cool winters. The climate is influenced by Iran's location between the subtropical aridity of the Arabian desert areas and the subtropical humidity of the eastern Mediterranean area [5]. Iran receives less than a third of the world's average precipitation [6]. Therefore, the need to identify and exploit non-conventional water resources such as domestic, agro-industrial and industrial is urgent.

According to WHO, in 2011 access to an improved water supply reached 98% in urban areas of Iran where more than two thirds of Iranians live, but the sanitation sector requires more investment provided that the plan would be wastewater reuse. Access to sewerage in urban areas was estimated at 19% in the late 1990s. Access to improved sanitation was estimated to nearly 100% in urban areas in 2019 [7]. In rural areas, cistern toilets are mostly used which are not connected to a sewer network. In terms of treatment techniques installed, conventional methods such as waste stabilization ponds (WSPs) and lagoons are widely applied for domestic and industrial wastewaters [8]. Recently, there has been some use of sequencing batch reactors (SBRs) for urban areas where land availability is scarce. Other methods such as membrane bioreactors and chemical treatment are employed as well.

However, since Iran still faces an economic crisis, the use of natural treatment systems is gaining more attention. There are already few examples of nature-based solutions (NBS) utilization, in particular constructed wetlands (CW) in Iran for industrial and domestic wastewaters and even for oil refinery complexes. NBS are systems designed to give solution to our global environmental problems in a sustainable way, providing also a series of ecosystem services and other economic and social benefits [9, 10]. In this chapter, two case studies of CWs installed in the Northeast of Iran are presented. The case studies are in the Neyshabur and in Mashhad, two major cities in Northeast of Iran.

14.2 A Constructed Wetland Case Study for Glass Industry Wastewater Treatment

14.2.1 Design and Operation of the CW

Industrial wastewaters are considered an important environmental hazard and risk for both human society and the ecosystems. They typically have a complex and unstable composition compared to municipal wastewater, with a large variety of pollutants of different nature, such as organic matter, nutrients, solids, heavy metals, colour, turbidity, salinity, and other inorganic and toxic compounds [11–13]. Thus, the effective treatment and management of industrial wastewaters has many technical, economic and environmental challenge. Conventional wastewater treatment technologies such as filtration, activated sludge, membrane bioreactors, and/or chemical treatment are often ineffective towards meeting the effluent criteria. Advanced treatment schemes and technologies could provide a high effluent quality, but they typically require a high energy input, intensified processes, use of chemicals, have high operational costs, which all also translate to a larger environmental footprint [14, 15].

On the other hand, Constructed Wetlands (CW) are an established nature-based solution that has been applied for many different industrial effluents, e.g., produced water from oilfields [4, 16], refinery effluent [17], tanneries [13], agro-industries such as olive mills, cork trees processing [18–20], water contaminated with phenols, fuel additives and petroleum derivatives [21–23], among others. CW have an ecological character along with reduced operation and maintenance costs, minimum energy demand, and zero use of chemicals [14, 24]. Therefore, CW technology could also be an attractive option for glass production wastewater treatment.

Glass industry includes a variety of manufacturing facilities and products, generating wastewater from the manufacturing processes such as washing, cooling and cullet separation and grinding [25] that may contain oil, lubricants, glass splinters and silica particles, turbidity, dissolved salts and water treatment chemicals [25, 26]. Silica particles are usually in the form of soluble silica when it comes to contact with water ($H_2SiO_{3,4}$), and insoluble ($SiO_{3,4}$ or silicon dioxide) form [27].

A first CW for a glass manufacturing industry (Safety Glass Khorasan - SGK) in Mashhad (36^0 24^0 48.8^{00} N, 59^0 28^0 33.65^{00} E and 1043 m above sea level) [28, 10]. The industry consumes 30 m^3/day of freshwater and produces on the average 10 m^3/day wastewater. Prior to the CW construction, there was only a series of collection tanks, from where it was pumped out and regularly transported to a centralized wastewater treatment facility, bearing the related transportation and disposal costs. The average temperature during the study period was 14.1 °C (27 °C in summer and 7 °C in winter) and the total precipitation did not exceed 250 mm.

In order to reduce the wastewater management costs, a Horizontal Subsurface Flow Constructed Wetland (HFCW) was implemented and tested first at pilot scale [28]. The pilot-scale CW had two compartments: a settling tank with an up-flow filtration layer and a HFCW. Figure 14.1 shows a top view and a picture of the pilot

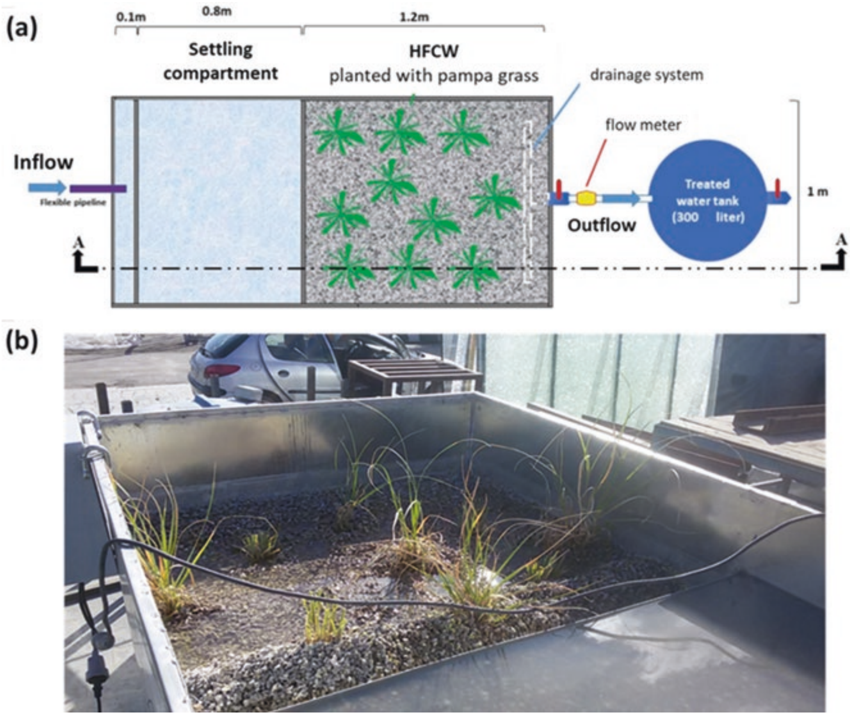


Fig. 14.1 (**a**) A top view and (**b**) a picture of the pilot-scale HFCW at the glass industry

system. The pilot unit was made of galvanized sheet and operated for 4 months testing two different flow rates, i.e., 75 and 120 L/d. Respective hydraulic retention times (HRT) were 13.3 and 8.3 days in the settling tank, and 6.7 and 4.2 days in the HFCW. The respective hydraulic loading rates (HLR) applied to the HSFCW were 6.3 and 10 cm/d. The system was fed with the glass industry wastewater every 6 h. The treated effluent was gravitationally collected to a 300 L plastic tank and was used to irrigate trees within the factory premises [28].

The settling tank dimensions were 0.9, 1, and 1.5 m (L, W, and D) and the water level was set at 1.1 m depth. An up-flow filtration layer of 15 cm thickness made of local natural cobbles (gradation 5–60 mm) was installed at the top of the settling tank to retain suspended solids and to promote natural flocculation of insoluble silica particles (SiO_2) in the filter. The HFCW compartment had dimensions of 1.2, 1, and 1 m (L, W, and D), was filled with local natural gravel (10–20 mm, porosity 38%) and planted with pampas grass (*Cortaderia Selloana*) at an initial density of 10 plants/m^2 [28]. Pampas grass is an indigenous plant species in the study area. The water level was adjusted 5 cm below the substrate surface.

The results of the pilot study indicated that not only the system designed can effectively treat the wastewater, but it also provided a final effluent appropriate for recycling in the industrial process. Hence, a full-scale CW system was designed and built at the SGK glass factory. The full-scale CW has a settling tank with two main

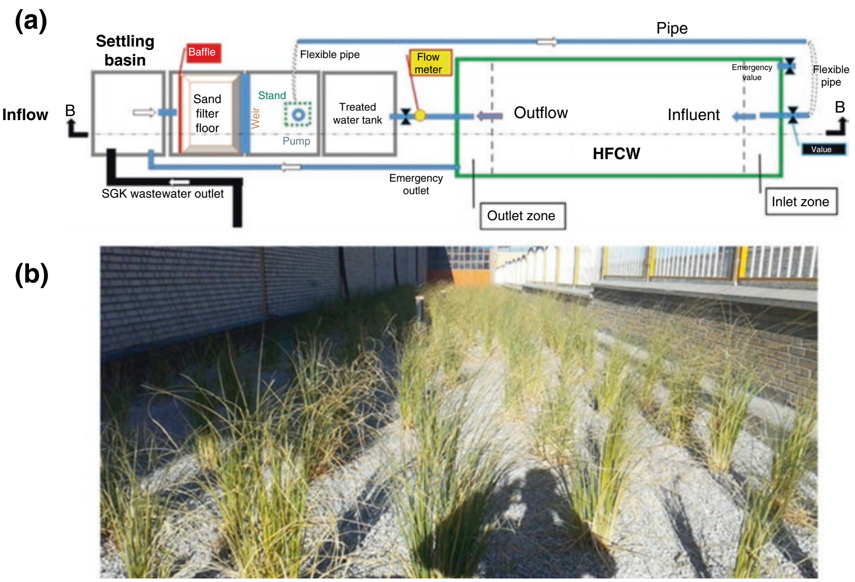


Fig. 14.2 (**a**) A top view and (**b**) picture of the HFCW system at the glass industry

settling compartments (each of area 8.75 m^2, L:W:D 3.5:2.5:4 m), followed by a HFCW (area 150 m^2, L:W:D = 30:5:1.1 m). A water reservoir (L:W:D = 3.5:2.5:4 m) was also installed to collect the treated water from the HFCW outflow and pump it for recycling in the glass manufacturing process [28]. Figure 14.2 shows an overview and a picture of the full-scale CW. The flow applied to the CW was gradually increased over a period of 8 months from 5 to 10 m^3/day, corresponding to HLR of 3.3 and 6.7 cm/d and HRT of 13.7 and 6.8 days (respective HRT in the settling tank were 13.3 and 6.7 days).

Samples were taken from the influent (IN), settling tank effluent (ST; i.e., influent to CW) and HFCW effluent (CW) in duplicates. Analyses were carried out to determine pH, chemical oxygen demand (COD), biological oxygen demand (BOD5), total suspended solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), temperature and salinity. A portable meter (LCD Digital, Meter Tester Filter Pen Stick Water Quality Purity) was used to measure pH. BOD5 was measured with respirometric bottles, COD with the open reflux method, TSS with the gravimetric method, TN and TP according to Standard Methods [29].

14.2.2 Treatment Performance

Table 14.1 shows the overall results obtained during the study period.

In terms of organic matter removal, BOD_5 and COD reached in total 90% removal, with effluent values below the standard for discharge to the sewage

Table 14.1 Average concentrations (C) of physico-chemical parameters at the inlet (IN), settling tank outlet (ST) and CW outlet (CW) and respective removal efficiencies (%) at each stage and in the system [28], along with the National effluent quality standards [30]

	HLR 6.3 cm/d						HLR 10 cm/d						National Standards
	IN	ST		CW		Total	IN	ST		CW		Total	
Parameter	C	C	%	C	%	%	C	C	%	C	%	%	C
BOD_5 (mg/L)	115	64.3	44.2	12.	80.7	89.2	128	59.1	53.7	12.9	78.2	89.9	100
COD (mg/L)	334	170	49.3	69.0	59.5	79.4	356	178	50.1	50.3	71.5	85.9	200
TSS (mg/L)	9058	260	97.1	45.4	82.5	99.5	9088	244	97.3	36.3	85.1	99.6	100
TDS (mg/L)	247	204	17.4	81	60.7	67.4	278	217	22.1	82	62.6	70.9	–
EC (μS/cm)	1317	1096	16.9	1001	8.7	24.1	1298	1136	12.5	915	19.6	29.6	–
pH (–)	9.59	8.74	–	7.62	–	–	9.47	8.38	–	7.56	–	–	6.5–8.5

network, while most of the organic matter is removed in the wetland stage. The performance was steady throughout the monitoring period despite the increase of the HLR. The load applied was 4.7–9.0 g $BOD_5/m^2/d$ and 12.9–25.9 g $COD/m^2/d$, based on the flow rate (5–10 m^3/day), while 4.3–8.0 g $BOD_5/m^2/d$ and 11.9–22.7 g $COD/m^2/d$ were removed in the system [28]. It is also obvious that the glass production process produces high solids content. Most of the TSS is removed in the settling tank, while almost complete removal takes place in the system. The CW showed an excellent TSS removal, which appears to be a major pollutant in this industrial wastewater. The main goal of the primary settling stage is to remove the TSS from the raw wastewater in order to prevent clogging of the downstream HFCW. The buffering capacity of the system was verified, since the effluent pH value was around the neutral values. A similar low content of nutrients was also found in the inflow, probably completely utilized by plants for their growth needs.

Though the local standards apply for discharge to the sewage network, the aim of the study was to recycle the treated wastewater onsite back to the industrial processes. The stable effluent quality with BOD_5, COD, and TSS concentrations below 15, 50, and 25 mg/L, respectively, indicates that the effluent could be reused in the manufacturing processes. The overall removal efficiency did not change even after the increased HLR over the first months of continuous operation, indicating the high treatment capacity of the tested design. This study was the first one applied for glass industry wastewater and demonstrates that this sustainable technology can be an effective and sustainable solution for such an industrial effluent under this arid climate.

14.3 A Constructed Wetland Case Study for Dormitory Wastewater Treatment

14.3.1 Design and Operation of the CW

Another successful CW system was built at the Neyshabor University in Neyshabor (360 15.09′ 89” N, 580 47.41′ 50″ E and 1249 m above sea level, a city in Razavi Khorasan Province, capital of the Neyshabor County. The climate of the area is dry and warm with a four-season region. The average temperature during the study period (Oct 2018 to Oct 2019) was 19.1 °C (33.2 °C in summer and 9.4 °C in winter) with a total precipitation of 222 mm. The Neyshabor University is a public Institution that hosts several faculties and many dormitories [43]. One of the dormitories for up to 200 students was selected for this case study, with a recorded average daily water consumption of 20 m^3/day, corresponding to approximately 133 L/PE/day (population equivalent). Before this project, there were only simple septic tanks for wastewater management. Thus, there was a need for an efficient, cost-effective and sustainable wastewater management process that would also allow for the treated effluent reuse in irrigation. A full-scale CW system was built in 2018 to

Fig. 14.3 Pictures of (**a**) the VFCW bed and (**b**) the HFCW bed of the hybrid CW system at the Neyshabor University

test and demonstrate its performance for dormitory wastewater treatment. The CW design includes an anaerobic baffled reactor (ABR), a vertical flow constructed wetland (VFCW) and horizontal subsurface flow constructed wetland (HFCW). Figure 14.3 shows a picture of this hybrid CW system.

The ABR is a reinforced concrete tank (L:W:D of 13.2, 3.6, 3.0 m). The water level is set at 2.7 m from the bottom, resulting in an effective holding volume of 108 m^3. It has three chambers (50:25:25% volume per chamber); the first chamber acts a settling tank for solids removal, a process that continues in the other two chambers along with the anaerobic digestion. The last chamber is equipped with a submersible pump that feeds the second stage VFCW. On top of the ABR, there are two access manholes and three standing ventilation pipes for gas release.

The CW basins have a 45° band slope. Both bottom and bands are covered with a compacted layer of fine sand and clay and an impermeable HDPE liner (1.5 mm), protected via a geotextile sheet. The VFCW has a surface of 200 m^2 (L:W = 10 × 20 m) and contains three gravel layers from bottom to top; a cobbles drainage layer (grain size 20–63 mm), a coarse gravel layer (grain size 5–15 mm) and a fine gravel layer (grain size 2–5 mm) with respective thicknesses of 30, 20, and 60 cm. A 20 cm freeboard is considered. The water level in the VFCW is maintained 20 cm below the gravel surface through a water level control chamber. The partially saturated bed is selected to allow for gravity flow to the HFCW, promote an anaerobic environment at the bottom, and to maintain the water in contact with the plant roots during the University summer break (July to August), when the dormitory is mostly empty. A feeding pipe network on top of the VFCW distributes the wastewater uniformly across the bed surface through 8 feeding points, while a perforated drainage pipe at the bottom of the downstream width side collects the treated water. The VFCW area is divided into two cells to allow for alternate feeding and resting periods. The right cell is fed from Friday noon to Tuesday noon and the left cell from Tuesday noon to Friday noon. This feeding regime is typical for the VFCW design and allows for the restoration of the aerobic conditions after wastewater application [24].

The partially treated wastewater from the VFCW flows with gravity to the HFCW. The HFCW has a surface of 250 m^2 (L:W = 25 × 10 m) contains a gravel layer (grain size 8–20 mm) of 1 m thickness with a freeboard of 20 cm and the water level was maintained 5 cm below the surface. The substrate porosity in both CW beds is approx. 30%. The HFCW has an inlet and outlet zone each with 20 cm length, containing large gravel (20–63 mm), to allow for the uniform distribution and collection of the wastewater and prevent media clogging. The final treated effluent is collected in an underground tank (160 m^3), where it is pumped out for reuse, i.e., for landscape irrigation within the campus and irrigation of non-bearing trees. The VFCW was planted with giant reeds (*Arundo donax*) and pampas grass (*Cortaderia selloana*) in its perimeter, while common reeds (*Phragmites australis*) were planted in the HFCW. All species all native and can be found in the natural wetlands of the Neyshabor area.

The HRT in the ABR, VFCW and the HFCW were approximately 5.4, 2.5 and 4 days, respectively, and the total HLR was 5 cm/day considering the net treatment area of the three stages, or 0.42, 0.20 and 0.08 m/d for each respective stage. The average organic loading rate (OLR) applied to the ABR was 131.1 g $BOD_5/m^2/d$ or 196.7 g $COD/m^2/d$.

Sampling started after the third operation month of the facility to allow for plants' establishment. Samples were taken in duplicates monthly for one full year from four different points, i.e., raw wastewater, ABR effluent, VFCW effluent and HFCW effluent. The laboratory of the Neyshabor Wastewater Treatment Plant was assigned to take samples during the period of the study.

14.3.2 Treatment Performance

Table 14.2 shows the average pollutant concentrations at the inlet (IN) of the facility and at different points, i.e., ABR effluent (ABR), effluent of the VFCW (VF), and effluent of the HFCW (HF), along with the national standard for wastewater discharge.

TSS removal in the ABR alone reached 54.8% with a stable performance during the monitoring period, while organic matter removal was 47.9% for BOD_5 and 46.4% for COD. The ABR is an effective primary treatment unit, due to its easy and

Table 14.2 Average values of pollutants concentration at the various sampling points, i.e., influent (IN), ABR effluent (ABR), VFCW effluent (VF) and HFCW effluent (HF)

Parameter (*n* = 12)	IN	ABR	VF	HF	National standard
BOD_5 (mg/L)	311	162	75.4	34.5	100
COD (mg/L)	467	250	145	65.5	200
TSS (mg/L)	466	210.4	113	36.3	100
PO_4-P (mg/L)	13.4	10.4	6.8	4.9	–
NH_4-N (mg/L)	20.1	15.1	9.1	6.7	–
NO_3-N (mg/L)	15.2	12.6	8.5	5.2	11.3
pH (–)	7.45	7.75	7.92	8.02	6.5–8.5
DO (mg/L)	1.64	1.84	2.6	1.3	2
Temperature (°C)	22.0	21.1	20.7	21.2	–
TDS (mg/L)	1366	1343	1243	1197	–
EC (mS/cm)	2.08	1.94	1.69	1.49	2.97
Total coliforms ($\log_{10}$MPN/100 ml)	5.18	5.12	3.89	2.75	3

simple operation and low mass production under warm climates [31], reaching high removal rates for organic matter and solids range, limiting this way the organic and suspended matter load to the hybrid CW and reducing this way the clogging risk in the long-run [31, 32].

The hybrid CW system has a high performance in the treatment of the dormitory wastewater. The removal efficiency for BOD_5, COD, TSS, PO_4-P, NH_4-N, and NO_3-N reached 88.9%, 86.0%, 92.2%, 63.5%, 66.5%, and 65.7%, respectively, during the first operational year. The tested design was found to perform better for most parameters than similar VF-HF designs reported in the literature [33–35]. The modification of keeping the VFCW partially saturated seems to have assisted the system in a higher nitrate removal, as is also elsewhere reported for a similar arid climate [36]. The removal of TC (99.99% or 2.43 log units) also indicates that disinfection is not necessary since the effluent TC content was below the limit value, as it is generally reported for hybrid CW systems [37]. As Fig. 14.3 indicates, the effluent values of the parameters mentioned in the national standard for effluent reuse were always below the limit values and the system showed a steady performance throughout its first year of operation.

The VFCW received an inlet OLR of 16.2 g BOD_5/m^2/d and 25 g COD/m^2/d, nitrogen load of 1.51 g NH_4-N/m^2/d and 1.3 g NO_3-N/m^2/d, while the removed loads were 10.2 g BOD_5/m^2/d, 13.5 g COD/m^2/d, 0.8 g NH_4-N/m^2/d, 0.6 g NO_3-N/m^2/d, 0.49 g PO_4-P/m^2/d and 12 g TSS/m^2/d. TSS were further reduced in the VFCW, where suspended solids are retained via filtration and sedimentation [24]. Organic matter removal was 53.5% for BOD_5 and 42.2% for COD and NH_4-N removal reached 40.0%. The VFCW design and its feeding regime (i.e., wastewater batches applied across the surface) creates aerobic conditions at the top that promote organic matter oxidation and nitrification [24]. Moreover, NO_3-N was reduced by 32.8% in the VFCW resulting in an average effluent of 8.5 mg/L, indicating the positive effect of a partially saturated bed to create an anaerobic environment that promotes denitrification [36, 38, 39]. A lower removal was found for PO_4-P (34.3%), which is expected for VFCW systems, since phosphorus retention is mostly related to abiotic processes [24]. Also, a reduction of TC by 1.24 log units (or 94.1%) to an average effluent value of 3.88 log units was also detected. VFCWs are in general more efficient than HFCW in pathogens removal, possibly due to the finer materials used and the higher dissolved oxygen concentrations [37].

The HFCW was the polishing stage of this facility. The HFCW operated at a HLR of 0.08 m/d with an OLR of 6.0 g BOD_5/m^2/d or 11.6 g COD/m^2/d, nitrogen load of 0.73 g NH_4-N/m^2/d and 0.68 g NO_3-N/m^2/d. The HRT of 4 days is lower than typically reported range (4–15 d) for this CW type for stronger municipal wastewater or industrial effluents [13, 18–20, 28]. The HFCW received an influent TSS of 113 mg/L providing an average effluent of 36.3 mg/L, corresponding to 67.9% removal or of 6.1 g TSS/m^2/d removed. The average TSS effluent value was below the national limit for effluent reuse throughout the study period, while the effluent pH also remained within the regulated range of 6.5–8.5. Organic matter removal was 54.2% for BOD_5 and 54.7% for COD with respective load removal of 3.3 g BOD_5/m^2/d and 6.3 g COD/m^2/d, providing respective effluent values of 34.5 and 65.5 mg/L, both also below the national limit values for effluent reuse. A 26% ammonia nitrogen removal was found but nitrate removal was higher (38.5%) with respective effluent concentrations of 6.7 and 5.2 mg/L. The HFCW generally promotes anaerobic conditions that favour denitrification, thus a lower NH_4-N removal than NO_3-N removal is generally reported in HFCW [34, 40]. This is the reason the HFCW is often used after the VFCW in order to denitrify the typically nitrified VFCW [34]. Since the average NO_3-N effluent value was always below the limit value for effluent reuse demonstrates that the HFCW was successful in its main goal as a denitrification step. Moreover, a lower PO_4-P removal was found (30.3%) with a respective average effluent of 4.9 mg/L, which is again more or less expected [34, 41]. Finally, TC were further reduced by 1.14 log unit.

Overal, the tested hybrid CW system showed a good performance in the treatment of the dormitory wastewater. The total removal for BOD_5, COD, TSS, PO_4-P, NH_4-N, and NO_3-N reached 88.9%, 86.0%, 92.2%, 63.5%, 66.5%, and 65.7%, respectively. As already indicated in the literature, the majority of the organic matter is removed in the first treatment stages of hybrid CW systems. Organic matter degradation requires an aerobic environment, hence the VF system performs better than the HF design, with the latter generally promoting anaerobic conditions as a saturated bed [14, 42]. The tested hybrid design was found to perform better for most parameters compared to other VF-HF designs [33–35]. The modification of the partially saturated VFCW apparently assisted in the higher nitrate removal, as is also elsewhere reported for a similar arid climate [36]. The TC removal (99.99% or 2.43 log units) also indicates that disinfection is not necessary since the effluent TC was below the limit value, as it is also reported for hybrid CW [37]. The effluent values of the parameters mentioned in the national standard for effluent reuse were always below the limit values and the system showed a steady performance during its first year of operation.

14.4 Conclusion

In this chapter, two different constructed wetland case studies are presented that have been implemented in Iran. Both refer to full-scale CW systems; one system for domestic wastewater/greywater from a University dormitory and another one for an industrial effluent (glass industry). Both wetland projects have been successful, i.e., they have achieved the treatment goals under the dry climate of northern Iran. The first CW system showed that this sustainable technology can be efficiently applied in small and medium communities and provide a treated effluent quality that can be safely reused for irrigation of green spaces. The performance of the CW applied for wastewater originated from a glass industry is also promising, since it allowed its recycling in the manufacturing processes, reducing this way the freshwater consumption of the industry. In simple words, the treated effluent in both cases is further valorized, either in irrigation and/or recycling, indicating the important role of CW technology in a circular water management in water scarce areas.

References

1. Šereš M, Innemanová P, Hnátková T, Rozkošný M, Stefanakis AI, Semerád J, Cajthaml T (2021) Evaluation of hybrid constructed wetland performance and reuse of treated wastewater in agricultural irrigation. Water 13(9):1165. https://doi.org/10.3390/w13091165
2. Echchelh A, Hess T, Sakrabani R, Prigent S, Stefanakis AI (2021) Towards agro-environmentally sustainable irrigation with treated produced water in hyper-arid environments. Agric Wat Manage 243:106449
3. Hasanean HM (2004) Middle East meteorology. Available online: http://www.eolss.net. Accessed 7 Aug 2021
4. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
5. Amiri MJ, Eslamian SS (2010) Investigation of climate change in Iran. J Environ Sci Technol 3(4):208–216
6. Vaghefi SA, Keykhai M, Jahanbakhshi F, Sheikholeslami J, Ahmadi A, Yang H, Abbaspour KC (2019) The future of extreme climate in Iran. Sci Rep 9(1):1–11
7. WHO (World Health Organization) (2019) WHO global water, sanitation and hygiene: annual report 2018 (No. WHO/CED/PHE/WSH/19.147). World Health Organization, Geneva
8. Daee M, Gholipour A, Stefanakis AI (2019) Performance of pilot horizontal roughing filter as polishing stage of waste stabilization ponds in developing regions and modelling verification. Ecol Eng 138:8–18
9. Stefanakis AI, Calheiros CSC, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sustainab. https://doi.org/10.1007/s43615-021-00022-3
10. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Piro P, Palermo SA, Turco M, Pirouz B, Stefanakis A, Regelsberger M, Ursino N, Carvalho PN (2021) Management of Urban Waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334

11. Hadad HR, Maine MA, Bonetto CA (2006) Macrophyte growth in a pilot-scale constructed wetland for industrial wastewater treatment. Chemosphere 63(10):1744–1753
12. Stefanakis AI (2018) Constructed wetlands for industrial wastewater treatment, 1st edn. Wiley, Chichester
13. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
14. Stefanakis AI (2016) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: McKeown AE, Bugyi G (eds) Impact of water pollution on human health and environmental sustainability. IGI Global, Hershey, pp 281–303. https://doi.org/10.4018/978-1-4666-9559-7.ch012
15. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11(24):6981. https://doi.org/10.3390/su11246981
16. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, UK, pp 25–42
17. Mozaffari MH, Shafiepour E, Mirbagheri SA, Rakhshandehroo G, Wallace S, Stefanakis AI (2021) Hydraulic characterization and removal of metals and nutrients in an aerated horizontal subsurface flow "racetrack" wetland treating oil industry effluent. Water Res 200:117220
18. Tatoulis T, Stefanakis AI, Frontistis Z, Akratos CS, Tekerlekopoulou AG, Mantzavinos D, Vayenas DV (2017) Treatment of table olive washing water using trickling filters, constructed wetlands and electrooxidation. Environ Sci Poll Res.:1085–1092. https://doi.org/10.1007/s11356-016-7058-6
19. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
20. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2020) Treatment of cork boiling wastewater using a horizontal subsurface flow constructed wetland combined with ozonation. Chemosphere 260:127598
21. Stefanakis AI, Seeger E, Dorer C, Sinke A, Thullner M (2016) Performance of pilot-scale horizontal subsurface flow constructed wetlands treating groundwater contaminated with phenols and petroleum derivatives. Ecol Eng 95:514–526
22. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
23. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10:127. https://doi.org/10.3390/app10010127
24. Stefanakis AI, Akratos CS, Tsihrintzis VA (2014) Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment, 1st edn. Elsevier Publishing, Amsterdam
25. Werner V (1994) Glass chemistry, 2nd edn. Springer Berlin and Heidelberg GmbH & Co. K, Germany
26. Kang S-K, Choo K-H (2003) Use of MF and UF membranes for reclamation of glass industry wastewater containing colloidal clay and glass particles. J Membr Sci 223(1–2):89–103
27. Fernandez LD, Lara E, Mitchell EA (2015) Checklist, diversity and distribution of testate amoebae in Chile. Eur J Protistol 51(5):409–424
28. Gholipour A, Zahabi H, Stefanakis AI (2020) A novel pilot and full-scale con- structed wetland study for glass industry wastewater treatment. Chemosphere 247:125966
29. APHA (2012) Standard methods for the examination of water and wastewater, twentieth, 2nd edn. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC
30. IEAP (2008) Environmental regulations and standards of Iran. Iran Global Environmental Law, Tehran

31. Liu R, Zhao Y, Doherty L, Hu Y, Hao X (2015) A review of incorporation of constructed wetland with other treatment processes. Chem Eng J 279:220–230
32. Knowles P, Dotro G, Nivala J, García J (2011) Clogging in subsurface-flow treatment wetlands: occurrence and contributing factors. Ecol Eng 37:99–112
33. Pan J, Zhang H, Li W, Ke F (2012) Full-scale experiment on domestic wastewater treatment by combining artificial aeration vertical- and horizontal-flow constructed wetlands system. Water Air Soil Pollut 223:5673–5683
34. Vymazal J (2013) The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development. Water Res 47:4795–4811
35. da Costa JF, Pinto Martins WL, Seidl M, von Sperling M (2015) Role of vegetation (Typha latifolia) on nutrient removal in a horizontal subsurface-flow constructed wetland treating UASB reactor–trickling filter effluent. Wat Sci Technol 71(7):1004–1010
36. Alwahaibi B, Jafary T, Al-Mamun A, Baawain MS, Aghbashio M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod. 296(126558). https://doi.org/10.1016/j.jclepro.2021.126558
37. Stefanakis AI, Akratos CS (2016) Removal of pathogenic bacteria in constructed wetlands: mechanisms and efficiency. In: Ansari AA, Gill SS, Gill R, Lanza G, Newman L (eds) Phytoremediation, vol 4. Springer International Publishing, Switzerland, pp 327–346
38. Kim B, Gautier M, Prost-Boucle S, Molle P, Michel P, Gourdon R (2014) Performance evaluation of partially saturated vertical-flow constructed wetland with trickling filter and chemical precipitation for domestic and winery wastewaters treatment. Ecol Eng 71:41–47
39. Silveira DD, Belli Filho P, Philippi LS, Kim B, Molle P (2015) Influence of partial saturation on total nitrogen removal in a single-stage French constructed wetland treating raw domestic wastewater. Ecol Eng 77:257–264
40. Hua Y, Peng L, Zhang S, Heal KV, Zhao J, Zhu D (2017) Effects of plants and temperature on nitrogen removal and microbiology in pilot-scale horizontal subsurface flow constructed wetlands treating domestic wastewater. Ecol Eng 108:70–77
41. Sehar S, Naem SS, Perveen I, Ali N, Ahmed S (2015) A comparative study of macrophytes influence on wastewater treatment through subsurface flow hybrid constructed wetland. Ecol Eng 81:62–69
42. He Y, Peng L, Hua Y, Zhao J, Xiao N (2018) Treatment for domestic wastewater from university dorms using a hybrid constructed wetland at pilot scale. Environ Sci Pollut Res 25:8532–8541
43. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106–360

Chapter 15
Research and Case Studies of Sludge Treatment Wetlands in Hot and Arid Climates: Experiences and Opportunities for Sustainable Sludge Management

Alexandros Stefanakis, Tahra Talib Al-Rashdi, and Mushtaque Ahmed

Abstract Many countries and regions under hot and arid climates suffer from a continuously growing pressure on their limited freshwater resources, which are subsequently degrading. In this regard, proper wastewater management could be a new water source in the local and regional water balance. However, wastewater treatment processes result in the production of a sludge by-product that requires additional treatment. Sludge management is typically a costly and complex process due to the needed mechanical equipment and the large amount of energy input. The sustainable treatment technology of Constructed Wetlands is viewed as an ideal nature-based solution for sludge management that can reduce the total environmental footprint and also provide a beneficial end-product. This chapter provides an overview of the current experiences on Sludge Treatment Wetlands technology in the Middle East. Research projects and few existing case studies for municipal and industrial sludge dewatering are presented in order to highlight the technical feasibility of this technology under the hot and arid climate of the Middle East.

Keywords Wastewater sludge · Nature-based solutions · Constructed wetlands · Vertical flow · Sludge treatment wetlands · Sludge treatment reed beds · Sludge dewatering · Hot and arid climate · Reuse

A. Stefanakis (✉)
Laboratory of Environmental Engineering and Management, School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece

EURECA-PRO – The European University on Responsible Consumption and Production, Chania, Greece
e-mail: astefanakis@tuc.gr

T. T. Al-Rashdi · M. Ahmed
Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Oman

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_15

15.1 Introduction to Sludge Management

One of the main operational challenges of wastewater treatment plants (WWTPs) is the production of a by-product material known as sewage sludge. Sludge is produced in large volumes along the treatment stages of WWTPs, such as [1]: (i) in the primary sedimentation (primary sludge), (ii) in the biological treatment stage, e.g., aeration tanks, and the secondary sedimentation (secondary sludge), as well as in the pre-treatment (screens, grit removal tanks). Primary and secondary sludge are often mixed and treated together (mixed sludge), while an advanced treatment stage can also produce tertiary sludge [2]. The origin of sludge is the same as for the respective wastewater, i.e., households, municipal areas, commercial centers, industrial facilities, agro-industries, surface runoff and stormwater. Sludge volumes keep increasing due to the increase in population that is connected to WWTPs and the adoption of stricter environmental legislation [3].

Typical sludge production in activated sludge plants, which is the most widely applied wastewater treatment method, can reach 2.5 kg per person equivalent (PE) per day [2]. For example, a population of 100,000 inhabitants, would produce a sludge volume up to 250 t/day. Municipal sludge production in the European Union (EU) reached 8 million tons in 2016 [4, 5], while a further increase was expected in 2021 with up to 13 million tons of dry solids (ds) [6]. Considering the wastewater volume that is treated in a WWTP, the sludge volume represents only a very small fraction (usually smaller than 1%). However, the total cost for sludge handling often accounts for more than 50% of the total operation costs of the WWTP [2]. This highlights the importance of implementing an efficient and cost-effective sludge management plan and technology.

Sludge is a glutinous watery material that is produced during aerobic or anaerobic wastewater treatment processes. Activated sludge plants generate a sludge material that contains high contents of nutrients and organic matter with high thermal value and a high moisture content up to 98–99% [2] and organic solids, along with other pollutants such as heavy metals, synthetic organic compounds, and microorganisms. Anaerobically digested sludge can have an even higher moisture content. Therefore, direct sludge disposal to the environment is not recommended and usually legally prohibited since it could lead to serious environmental risks such as public health hazards, pollution of surface and ground water bodies and even air pollution.

However, valuable compounds can also be found in sludge such as organic carbon, and nutrients (nitrogen and phosphorus). Ammonia nitrogen can be the major nitrogen form in sludge, which enables its use as fertilizer. The sludge composition depends on its origin, the treatment stage where it is produced and the pollutant load and heavy metal concentration of the treated wastewater. The composition and characteristics of sludge provide key information that is necessary in sludge management, since it defines the most effective treatment method [2].

15.1.1 Sludge Treatment Processes

Sludge treatment is a required process before its final disposal or reuse and aims its volume reduction and substance degradation. Widely used conventional processes include sludge thickening, dewatering, and drying. Figure 15.1 shows the sludge solid content (% of dry mass) during the different sludge dewatering processes. After thickening, the sludge mass can be reduced up to 70% of the initial volume, resulting in a total solids content of 2–3%. After dewatering, the water content is further reduced, and the solids content increases up to 18–20%. Finally, sludge drying, significantly reduces the water content to below 10%. Thermal drying has a high energy consumption; drying of 1 ton of sludge with 10% solids (thus 90% water content) requires 2.5–3.0 × 10^6 kJ of thermal energy [2]. Therefore, it is crucial to identify a sludge drying method that would reduce the water content with minimal or even zero external energy demand.

There are many technologies and methods available for sludge dewatering and drying such as mechanical systems (e.g., vacuum filters, gravity belt thickening, filter belt press, gravity thickening, centrifuges), direct drying systems (e.g., rotating drums, lamps, belt dryers, spray dryers, solar energy dewatering), indirect drying systems (e.g., rotaplate indirect dryer, kneading and self-cleaning disc dryer), fluidized bed dryers, drying and incineration, aerobic and anaerobic digestion, composting and sand beds [2, 7, 8]. However, most of these methods possess a high energy input as well as a complex and expensive operation and maintenance, requiring skilled staff and the use of chemicals [9], that prohibit their use in WWTPs with relatively small capacity or in low-income regions. Hence, alternative cost-effective and environmentally friendly dewatering solutions are in high demand in the field of sludge management.

Considering also the gradually adopted circular approach that sees waste as a valuable resource [10], sustainable sludge management options are now required. In

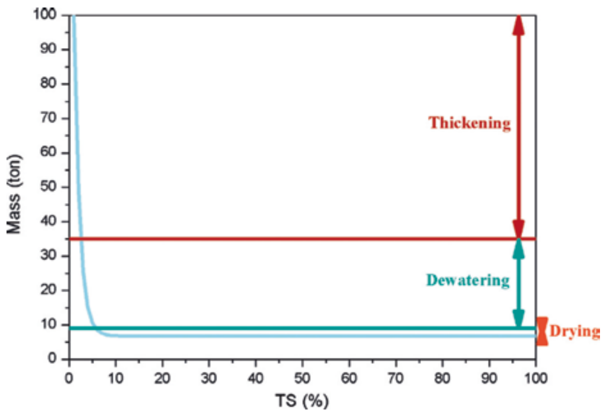


Fig. 15.1 Various sludge treatment processes and total solids (TS) content (%) and mass (ton) variations [2]

a circular economy, sludge from WWTPs is not considered any more a waste but a beneficial resource that should be further exploited to valorize its nutrient and thermal content rather than disposing sludge to landfills or use the energy-consuming incineration [6]. Since sewage sludge contains organic matter and nutrients, it is used as a soil amendment, as a fertilizer in agriculture, and in other environmental applications (e.g., forestry and land reclamation) after appropriate hygienization and stabilization processes [11–13]. In this context, nature-based solutions can provide the required options for sludge management with the desired characteristics [14, 15], such as the technology of sludge treatment wetlands (STWs) also known as sludge treatment reed beds (STRBs) [16].

15.2 Sludge Treatment Wetlands

Sludge treatment in constructed wetlands was first developed in the late 1980s. Today it is known a cost-effective nature-based solution with simple operation for the dewatering and stabilization of sewage sludge that can be applied at small and large scales [11, 17, 18]. Compared to mechanical dewatering and sludge disposal, STW technology typically has slightly higher investment costs but significantly lower operation costs [16]. A life cycle cost analysis and comparison between STW and mechanical technologies on the dewatering of activated sludge of 550 t ds/year showed that the STW system is indeed a cost-effective alternative with more than 50% reduction in operational costs [19, 20]. As an ecological engineering technology, STW do not require the use of polymer coagulants for the dewatering, while the minimum amount of required energy input, the absence of complex electromechanical equipment, and the use of natural materials and processes, make STW a sustainable and widely applicable treatment technology with a minimal carbon footprint [2, 20–22].

STW technology is an established technology for municipal sludge dewatering mostly in Europe and USA, e.g., it has been used in Denmark for almost 30 years [16, 23]. STW can also be found in France, Germany, Poland, Sweden, Norway and Spain; e.g., it is reported that more than 300 STW facilities are in operation in France [2]. Gradually, STW testing facilities and full-scale applications expand to other countries too, especially in Mediterranean countries, e.g., Greece, Spain, and Italy [24–29], where the climatic conditions are favorable for these systems, as also in tropical countries [30–32].

The key to sufficient STW efficiency is proper design and construction. However, despite the ongoing progress and the increasing research studies on STWs, there are still uncertainties on the system design, so there are not a generally accepted setup or design guidelines and the STW dimensioning is mainly based on empirical rules. STW design also depends on the sludge quality and type and on the local climatic conditions [2, 17]. Important information for the designers is the annual WWTP sludge production (tons of dry mass) and the sludge production duration. The most crucial design parameter is the determination of an appropriate sludge loading rate

(SLR; kg dm/m²/year), which is influenced by the climatic conditions. A STW facility operates in cycles; each cycle consists of a loading period (few days up to few weeks) followed by a resting period (usually longer than the loading period). Therefore, the accurate design (i.e., the required surface area and the number of beds), the proper selection of the SLR and the applied loading and resting period durations are essential [18]. These two characteristics will ultimately determine the life span of each operation phase. However, as mentioned, feeding patterns and resting periods are not standardized.

Based on previous experiences, STW can treat most types of sludge with solids contents between 0.1 and 5% [2]. Specific sludge types, especially those of industrial, i.e., non-domestic, origin may, in general, be difficult to dewater and sometimes unsuitable for an STRB system, e.g., sludge rich in oil and fat. Industrial sludge is considered a more difficult application and technically more challenging for effective dewatering, since it may contain heavy metals, nutrients, hazardous organic compounds, oil, and fats at much higher levels than typical sludge of domestic origin. This is why the vast majority of STRB facilities worldwide are designed for the dewatering of domestic sludge. However, there are already completed and ongoing studies on dewatering of different industrial sludges in STWs [16, 33].

The overall STW concept is similar to that of a vertical flow constructed wetland [2, 23]. A STW bed is a concrete or trapezoidal earthen basin [9, 25] with its bottom covered by an impermeable material, such as a high-density polyethylene (HDPE) geomembrane. The basin is filled with gravel and sand of different sizes and thicknesses [2], while on top of the substrate layer, native wetland plant species are planted, such as common reeds (*Phragmites australis*). A distribution pipe network spreads the feed sludge across the surface of the bed, where sludge is dewatered through passive vertical drainage and evapotranspiration (Fig. 15.2) [9, 34, 35]. A drainage pipe network is placed into the bottom cobble layer and collects the drained

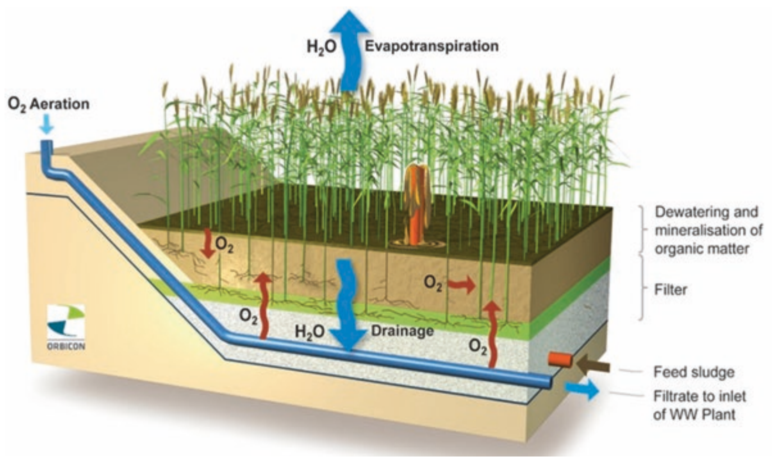


Fig. 15.2 Cross-section of a STW showing the sludge layer, the filter media and the feeding and drainage network (Source: Orbicon)

water. The drainage network is connected to vertical pipes that facilitate the passive aeration of the bed, which has been found to be beneficial for the dewatering performance of the system [2, 35].

Vegetation and passive ventilation provide favourable conditions for the conversion of degradable organic matter to a more stable humic form [26, 36]. The dewatering process and the organic matter mineralization decrease the sludge volume, and the accumulated residual sludge is continuously incorporated into the filter media layer where the plants are established. As time passes, the depth of the mineralized residual sludge layer increases at an approximate accumulation rate of 10–15 cm/year, depending on the feed sludge quality [2]. Typically, after 8–12 (even up to 20) years of operation, the dewatered and mineralized residual sludge layer is removed from the beds and recycled as a fertilizer or as a soil conditioner, typically after a few months of further maturation [9, 11, 34, 37, 38]. Current experience has shown that STW can treat sludge of varying quality, having a comparable or even higher dewatering capacity than conventional dewatering systems.

Despite these advantages of STW technology, little to zero investigation has been carried for the implementation of this technology in hot and arid climates (e.g., in the wider Middle East region). Although the climatic conditions (high temperature) favour such a system and promote the dewatering process, little is reported so far in the international literature. Therefore, the goal of this chapter is to summarize the limited previous and ongoing activities and research projects in hot and arid climates, with focus on the region of Middle East. For this, an ongoing research project will be presented, along with the few available STW case studies.

15.3 Sludge Treatment Wetland Optimization Through Pilot Scale Experiments

One of the first integrated research projects on STW design optimization for hot and arid climates in the Middle East is currently ongoing in Oman by the Sultan Qaboos University. As for most countries in the region, wastewater and sludge management is a major concern due to the increasing technological requirements, continuous environmental degradation and the related high treatment costs. The established sludge management practice in Oman is dewatering in simple drying beds and then disposal to landfills.

In 2011, Haya Water (the governmental company for wastewater management) also established a composting facility to convert sludge to fertilizer (organic compost plant 'Kala') along with biodegradable horse manure and shredded garden and park waste. However, this plant has limited capacity and serves mainly the capital of the country (Muscat governorate), leaving remote areas with the only remaining option of sludge landfilling. In addition, of the ten WWTP that dispose the generated sludge to the compost facility, four are far from Muscat governorate (distances from 78 to 253 km), making sludge transportation a costly (i.e., 12 USD per ton of dried sludge) and time-consuming practice that also has a high carbon footprint.

Few research studies have been carried out on sludge production and characteristics in Oman. Baawain et al. [39] investigated the characterization of industrial sludge from the regions of Muscat (Rusayl Industrial Estate), Sohar (Sohar Industrial Estate) and Salalah (Raysut Industrial Estate), focusing on anions (Fluoride, Chloride, Nitrite, Bromide, Nitrate, Phosphate, and Sulfate) and heavy metals (Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Molybdenum (Mo), Nickel (Ni) and Zinc (Zn)). The concentrations of nitrate were the highest among other anions, while the concentrations of heavy metals were within the Omani standards except for Cd in Rusayl. Domestic sludge was also characterized by Baawain et al. [40]. In both studies, the results showed the possibility of reusing the sludge for agriculture.

Moreover, a five-year study by the Sultan Qaboos University studied the effect of kala compost on soil and crops (mainly cucumber). The physicochemical analysis showed that the heavy metals concentrations in soil and crops were within the international standards. The compost improved the physiochemical properties of soil such as water holding capacity and reducing soil bulk density. In addition to that, the crops were free of pathogenic bacteria. Kala compost proved to be a good conditioner and media for growth of plants, but it needs further monitoring to avoid any adverse impacts in the future [41].

Based on the Oman 2040 vision, the country's target is to have effective, balanced, and resilient ecosystems to protect the environment and ensure sustainability of natural resources in order to support the national economy. The vision focuses on the use of modern technologies in wastewater treatment and reuse in agriculture and energy production. Therefore, alternative ecological systems such as the STW are needed to allow for further sludge valorization. This research project is the first in the region to test sludge dewatering in STW. Haya Water has also shown interest in the development of this technology in the country as a decentralized option for sludge management.

The objective of this research project are: (i) better understand the dewatering processes in STW, (ii) identify the optimum SLR under the hot and arid climate of the region, (iii) evaluate the role of plants in the treatment, and (iv) measure and assess the greenhouse gas emissions of the STW and a simple sludge drying bed.

15.3.1 Materials and Methods

The study started in January 2021 with the setup of the pilot scale units. A total of 18 pilot units were built. Each unit consists of a plastic circular tank of 89 cm in height and 0.24 m^2 surface area and is filled from top to bottom with fine gravel (2–6 mm; porosity 43%; thickness 15 cm), medium gravel (15–25 mm; porosity 40%; thickness 15 cm) and a drainage layer of cobbles (40–60 mm; porosity 50%; thickness 5 cm). Above the substrate layer, there is a freeboard of 54 cm. Each unit was initially planted with four reed stems (*P. australis*). Figure 15.3 shows a general view of the experimental setup.

Fig. 15.3 The pilot Sludge Treatment Wetland units in Oman

Fig. 15.4 Pictures of the different gravel media during the construction of the pilot STW units

Two vertical tubes with open top are embedded in the bottom of the unit. Three different SLR are tested: 75, 100 and 125 kg ds/m^2/year. Each SLR is tested in three STW replicates, while each SLR is also tested in three replicates of unplanted beds. Sludge is collected from the Ansab WWTP in Muscat from the primary and secondary sedimentation and the aeration tank. Different operational cycles will be tested (feeding and resting days). Figure 15.4 shows the different media sizes in each pilot unit.

Samples are collected from the feed sludge and the residual sludge layer that is gradually formed on top of the gravel layer of each unit. Water that is drained at the bottom of each tank is also collected for analyses at various time points after fresh sludge application (10 min, 30 min, 1 h, 2 h, 1 day, 2 days). Sludge samples are analyzed for Total Solids (TS; %), Volatile Solids (VS; %TS), Loss of Ignition (LOI), Total Nitrogen (TN; mg/kg), NO_3-N (mg/kg), NO_2-N (mg/kg), Total Phosphorus (TP; mg/kg), heavy metals (Cd, Cu, Ni, Pb, Zn, Hg, Cr; mg/kg), pH, electrical conductivity (mS/cm), fats and oil content (mg/kg), E. coli, Total Coliforms and/or Salmonella spp (MPN/g). Drained water samples from each unit are analyzed for the Total Suspended Solids (TSS; mg/L), Total Dissolved Solids (TDS; mg/L), Volatile Suspended Solids (VSS; mg/L), COD (mg/L), BOD_5 (mg/L), NH_4-N (mg/L), NO_3-N (mg/L), SO_4^{-2} (mg/L), PO_4^{-3} (mg/L), pH, electrical conductivity (mS/cm).

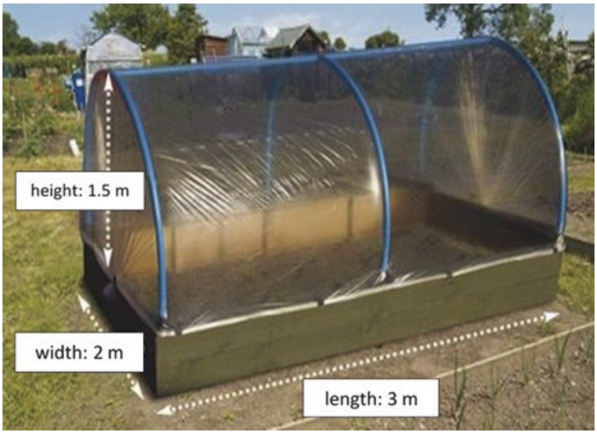


Fig. 15.5 The mesocosm STW design of the experimental setup

Once the pilot experiment is completed (after 2 years of operation), 2 larger STW mesocosms will be constructed of 6 m^2 surface (2 × 3 m) in order to test the experimental results under real operational conditions (Fig. 15.5). The same analyses will also be carried out in the mesocosms. In addition, greenhouse gas emissions will be measured. For this, the STW mesocosm units will be covered with a hanged cover (1.5 m in height). Four main greenhouse gases will be measured (CO_2, CH_4, NH_3, NO_X). There will be a 1-meter pipe connected to the cover from one side and to a multi gas analyzer (SKY8000) on the other side to allow the flow of air and take real time readings. The sampling of air will be taken every 2 h, i.e., (6–8) am, (8–10) am, (10–12) am, (12–2) pm, (2–4) pm and then (4–6) pm. These readings represent the whole day. Also, there will be a small fan to mix the air inside the covered STW. All the environmental conditions will be controlled.

Ultimately, the final residual sludge will be assessed regarding its quality according to the national standards in Oman for the reuse of sludge in agriculture (Table 15.1).

15.3.2 First Experimental Results

The pilot STW units were running for a short period (3 months) at the time of writing this chapter. A first commissioning period of approx. 2 months was applied during which the units were fed with light wastewater in order to allow for the establishment of the plants. Sludge application started in mid-March. Here the first experimental results are presented after six sludge feed cycles. The operation cycle of the units is 3 days feeding followed by 4 days resting. Table 15.2 shows the characteristics of the feed sludge. As it can be seen, the average TS is 1.6%, a value typical for a mixed sludge originating from primary and secondary sedimentation and the aeration tanks. The feed sludge is also rich in nutrients, while only few metals are detected.

Table 15.1 Conditions for the reuse of sludge in agriculture and land application in Oman (MECA MD145/93)

Metal	Maximum concentration (mg/kg ds)	Maximum application rate (kg/ha/year)	Maximum permitted concentration in soil (mg/kg ds)
Cadmium	20	0.15	3
Chromium	1000	10	400
Copper	1000	10	150
Lead	1000	15	30
Mercury	10	0.1	1
Molybdenum	20	0.1	3
Nickel	300	3	75
Selenium	50	0.15	5
Zinc	3000	15	300

After spreading of sludge there must be a minimum period of 3 weeks before grazing or harvesting of forage crops
Sludge use is prohibited:
- On soils whilst fruit or vegetables crops, other than fruit trees, are growing or being harvested
- For 6 months preceding the harvesting of fruit or vegetables which grow in contact with the soil and which are normally eaten raw
- On soils with a pH < 7.0

Table 15.2 Characteristics of the feed sludge quality

Parameter	**Average ± standard deviation (*n* = 6)**
TS (%)	1.67 ± 0.35
VS (%TS)	71.96 ± 4.72
pH	7.07 ± 0.23
EC (mS/cm)	2.27 ± 0.21
TKN (g/L)	1.11 ± 0.06
PO_4^{-3} (mg/L)	49.64 ± 9.13
Heavy metals (mg/kg)	**Average ± standard deviation (*n* = 5)**
As	nd
Zn	5.85 ± 1.66
Pb	0.11 ± 0.08
Co	nd
Cd	nd
Ni	0.54 ± 0.07
Fe	52.19 ± 4.55
Hg	nd
Mn	0.65 ± 0.10
Cr	0.46 ± 0.14
Cu	1.13 ± 0.13
B	1.50 ± 1.03
Al	25.98 ± 1.93

nd not detected

Table 15.3 Drained water volume (L) in the pilot units (average of triplicates) at different SLR expressed as percentage (%) of the feed sludge volume in total (2 months of operation) and during the first (March 2021) and fourth feeding cycle (April 2021)

	Total (L)		1st cycle (L)		4th cycle (L)	
SLR	Planted	Unplanted	Planted	Unplanted	Planted	Unplanted
75	13.0	49.9	34.3	38.1	0	52.3
100	17.2	52.5	26.5	49.2	8.9	53.2
125	24.9	45.2	41.2	47.1	13.6	40.8

Since the pilot units are in operation for only a few months, the sludge layer on top of the gravel layer is still under formation, of course more so in the units receiving the higher SLR. Thus, sludge samplings have not yet taken place. However, the first dewatering signs can already be seen. Table 15.3 shows the drained water volume expressed as percentage of the feed sludge volume. The effect of the SLR is clear as higher SLR results in higher drained water volume. There is also a first indication of the role of plants, as in the unplanted units approx. half of the feed sludge volume leaves the bed with drainage. This difference implies the increased evapotranspiration in planted units due to the water loss by plant to cover their growth needs [42]. Moreover, the data between the first and fourth feed sludge application show the increasing water losses since the plants' growth continues and the temperatures are also increasing approaching the summer season.

Overall, this first research project on STW under the hot and arid climate of the Middle East is expected to give the first deep and integrated insight that is necessary in order to further expand the use of these systems in the region with more accurate designs.

15.4 STW Case Studies in Hot and Arid Climates (Middle East and Australia)

In most countries in the region, sludge management consists in dewatering in simple unplanted drying beds. This system is a permeable basin that is loaded with sludge and produces the leachate at the bottom; thus, sludge drying is mostly taking place through evaporation and drainage. However, in these systems sludge is not stabilized nor sanitized, while the final solids content does not reach high values. It also has the disadvantage that dried sludge should be regularly removed from the bed, which means that it has a higher operation and maintenance needs and costs while the final sludge disposal remains problematic. Dry sludge from simple drying beds cannot be reused in agriculture since its organic fraction is not stabilized and the pathogenic microorganisms are not significantly decreased. Therefore, dried sludge needs further treatment before it desired reuse. On the contrary, the STW provides the advantage of a stabilized and mature residual sludge, while the basins do not need to be desludged frequently. In the following sections, the few existing STW case studies are presented. For most of these systems, detailed information is either not available or cannot be shared since many are private projects.

Fig. 15.6 The first STW system in Bahrain (Source: Blumberg Engineers)

15.4.1 Bahrain

Tests with STWs have been carried out in few countries in the Middle East, i.e., Egypt, Jordan and U.A.E., with very good performance results. The first system in Bahrain was built in Hidd to receive the excess sludge from a Moving Bed Biofilm Reactor (MBBR) wastewater treatment plant with a capacity of 1500 m^3/day (Fig. 15.6). This STW is in operation since 2012 [43].

15.4.2 Jordan

One of the first STW facilities is a pilot system built at the Al-Salt wastewater treatment plant in Jordan between 2011 and 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 [43, 44]. There were four unplanted drying beds each of 160 m^2 area that were retrofitted to STW beds in 2011. These beds received 8–10 m^3 of sludge with 2.5% ds from the nearby Al-Salt conventional wastewater treatment plant [44] (Fig. 15.7), in particular sludge from the aeration basin, the settling tanks and the multimedia filtration units.

After this demonstration system, a larger STW system is under construction at Wadi Hassan in Jordan (Ingenieurbüro Blumberg, Bovenden, Germany) for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The wastewater treatment plant (extended aeration system) has a capacity of 1600 m^3/day and produces 50 m^3/day of excess sludge with 3% dry solids content from the aeration basin and the primary and secondary settling tanks [43]. So far, excess sludge was transported from the treatment plant to a landfill for disposal, which is a labour and energy intensive practice with high associated costs. The facility includes a first step

Fig. 15.7 STW beds in Al-Salt wastewater treatment plant in Jordan [43, 44]

of sludge thickening, sludge drying beds for summer operation, and STW beds for winter operation (6 months per year). The selected SLR is 70 kg ds/m^2/year and the STW beds net treatment surface is almost 4000 m^2 (total facility area of 9250 m^2).

15.4.3 United Arab Emirates

A STW is also built in Al Khor industrial area in Dubai, UAE in 2007 and operated for more than 5 years (Fig. 15.8). This STW was used to dewater and mineralize the septic sludge from a nearby labour camp. Solar panels were installed above the STW for renewable energy production. The drained water from the STW was used to spray the solar panels for cooling and cleaning [43].

15.4.4 Qatar

Another STW facility was built in Qatar at the Al Sahara Sand Plant. The STWs receive the surplus sludge of a wastewater treatment plant using a Sludge Blanket Reactor with a capacity of 4000 m^3/day (Fig. 15.9). It is planned to use the final residual sludge as fertilizer [43].

15.4.5 Oman

The first STW system in Oman was built at the Six Senses Resort in Zighy Bay, Dibba in 2010 (Fig. 15.10). The resort has an onsite wastewater treatment plant (membrane bioreactor) that produces an excess sludge of 5 m^3/day or 33 tons dry solids/year [43]. The previous sludge management practice was transportation to a central sludge treatment facility, but this practice had a high cost for transportation and disposal and a high carbon footprint. Hence, the goal of this project was the onsite sludge treatment. The STW is already in operation for more than 10 years and

Fig. 15.8 The STW system in Al Khor industrial area in Dubai, UAE

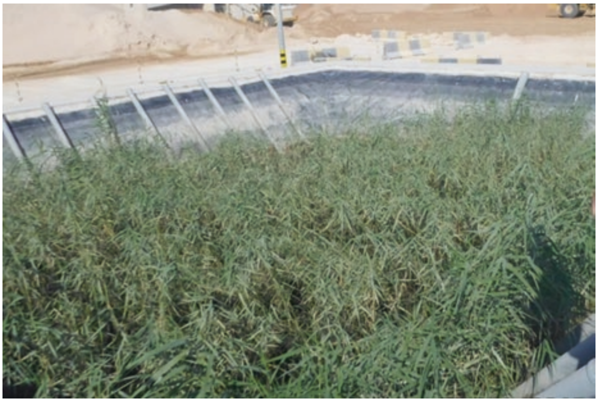


Fig. 15.9 The STW system at the Al Sahara Sand Plant in Qatar

is now well integrated into the natural landscaping of the 5-star eco-tourism resort. The dewatering proceeds using only natural processes without the use of any chemicals, while energy is consumed only for sludge pumping and loading onto the STW bed. It should be noted that this STW is located only 17 m away from the pool area of the resort and 70 m away from the villas and the residential rooms, with any complaints or nuisance for all these years.

Fig. 15.10 The STW system at the Six Senses Resort in Zighy Bay, Dibba, Oman [42]

Successful projects can also be found in Oman where the two-stage VFCW system has been implemented in three facilities [43, 45]. The first stage of this design (also known as French system) is a sludge mineralization bed, since it receives the raw wastewater without pre-treatment. Therefore, the operation of this VFCW bed is close to that of a STW system. The first facility in Oman receives 120 m^3/day and the second one 350 m^3/day [43]. Another such system is also built by Haya Water as an experimental plant at the wastewater treatment plant of Quriyat receiving 25 m^3/day [45]. The experiences from these VFCW system receiving raw wastewater (including the organic solids) have proven the capacity of this wetland system to accumulate and dewater the organic solids, which is a strong indication of the high potential for implementation of the STW design.

15.4.6 Australia

The application of the STW technology was also tested in the hot and arid climate of Australia, in particular in Wacol, Coolum and Pimpama in 2016–2019 [46]. The pilot trial in Wacol, Southeast Queensland included five STW beds each with a treatment surface area 1.2 m^2. It showed better efficiency rates, achieving SLR between 60 and 80 kg DS/m^2/year due to efficient airdrying and high plant evapotranspiration rates. The tests also revealed that local climatic conditions favoured a high dewatering efficiency, indicating the need for a modification of the loading patterns traditionally used in cooler climates in order to maintain optimal plant health and therefore system longevity [46]. The results showed that during the summer season with temperatures above 40 °C for long periods, moisture levels in the soil layer (located directly below the sludge residue buildup) can drop extremely fast to critical levels below 20%, affecting plant health when sustained for more than a few days at a time. The implementation of STW in hot climates showed that the fast and more efficient sludge drying allows for higher SLR application and shorter resting periods, which further allows for a smaller number of basins needed compared to systems in colder climates.

15.5 Conclusions

The technology of sludge treatment wetlands is a sustainable nature-based solution for sludge dewatering and drying from wastewater treatment plants [15]. Although, it is well established in many European countries, in North America and other parts of the world, the applications in hot and arid climates are rare so far. The use of STWs for sludge dewatering and drying in the vast Middle East region is extremely limited with less than 10 existing facilities. This is not a surprise considering that the technology of constructed wetlands in general is still a largely unknown technology in the Middle East. However, the hot and arid climatic conditions are favorable for the development of these systems, allowing for higher sludge loading rates to be applied due to higher evapotranspiration rates and efficient airdrying. STW are also a more beneficial solution with easier operation compared to traditional sludge drying beds, since sludge loads continue for years without the need to frequently remove and transport the dried sludge. However, despite the very limited market penetration of STW in the region, there is a handful of successful projects. This chapter presented the existing STW applications for municipal sludge dewatering in the Middle East region, as well as the preliminary results of an ongoing research study. The few case studies demonstrate not only the technical efficiency and feasibility but also the sustainable character of this treatment technology that can be easily implemented under these climatic conditions providing further options for a circular management of the residual sludge, e.g., reuse as fertilized in agriculture [15].

References

1. Metcalf E (2003) Wastewater engineering: treatment and reuse. McGraw Hill, New York, USA
2. Stefanakis AI, Akratos CS, Tsihrintzis VA (2014) Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment. Elsevier Publishing, Amsterdam
3. Fytili D, Zabaniotou A (2008) Utilization of sewage sludge in EU application of old and new methods – a review. Renew Sust Energ Rev 12:116–140
4. Bianchini A, Bonfiglioli L, Pellegrini M, Saccani C (2016) Sewage sludge management in Europe: a critical analysis of data quality. Int J Environ Waste Manag 18:226–238
5. European Commission (EC) (2020) Sewage sludge. https://ec.europa.eu/environment/waste/sludge. Accessed 14 Sept 2020
6. Salado R, Vencovsky D, Daly E, Zamparutti T, Palfrey R (2010) Environmental, economic and social impacts of the use of sewage sludge on land; part II: report on options and impacts; report by RPA. European Commission, DG Environment, Brussels, Belgium
7. Chen G, Yue PL, Mujumdar AS (2002) Sludge dewatering and drying. Dry Technol 20(4–5):883–916
8. Wakeman RJ (2007) Separation technologies for sludge dewatering. J Hazard Mater 144(3):614–619
9. Stefanakis AI (2015) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Impact of water pollution on human health and environmental sustainability. https://doi.org/10.4018/978-1-4666-9559-7.ch012

10. Nikolaou IE, Jones N, Stefanakis AI (2021) Circular economy and sustainability: the past, the present and the directions. Circ Econ Sustain. https://doi.org/10.1007/s43615-021-00030-3
11. Brix H (2017) Sludge dewatering and mineralization in sludge treatment reed beds. Water 9:160. https://doi.org/10.3390/w9030160
12. Olsson L, Larsen JD, Ye S, Brix H (2014) Emissions of CO2 and CH4 from sludge treatment reed beds depend on system management and sludge loading. J Environ Manag 141:51–60
13. Mantovi P, Baldoni G, Toderi G (2005) Reuse of liquid, dewatered, and composted sewage sludge on agricultural land: effects of long-term application on soil and crop. Water Res 39:289–296
14. Stefanakis AI, Calheiros CSC, Nikolaou I (2021) Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ Econ Sustain. https://doi.org/10.1007/s43615-021-00022-3
15. Oral HV, Radinja M, Rizzo A, Kearney K, Andersen TR, Krzeminski P, Buttiglieri G, Ayral-Cinar D, Comas J, Gajewska M, Hartl M, Finger DC, Kazak JK, Mattila H, Vieira P, Piro P, Palermo SA, Turco M, Pirouz B, Stefanakis AI, Regelsberger M, Ursino N, Carvalho PN (2021). Management of urban waters with nature-based solutions in circular cities – exemplified through seven urban circularity challenges. Water 13(23):3334. https://doi.org/10.3390/w13233334.
16. Nielsen S, Stefanakis AI (2020) Sustainable dewatering of industrial Sludges in sludge treatment reed beds: experiences from pilot and full-scale studies under different climates. Appl Sci 10:7446. https://doi.org/10.3390/app10217446
17. Nielsen S, Willoughby N (2005) Sludge treatment and drying reed bed systems in Denmark. Water Environ J 19:296–305
18. Uggetti E, Ferrer I, Llorens E, Garcia J (2010) Sludge treatment wetlands: a review on the state of the art. Bioresour Technol 101:2905–2912
19. Nielsen S (2005) Mineralisation of hazardous organic compounds in a sludge reed bed and sludge storage. Water Sci Technol 51:109–117
20. Nielsen S, Larsen JD (2016) Operational strategy, economic and environmental performance of sludge treatment reed bed systems – based on 28 years of experience. Water Sci Technol 74:1793–1799
21. Boruszko D (2018) Changes of the content of heavy metals and PAH's in sewage sludge treatment with reed bed lagoons. J Ecol Eng 2018(19):75–87
22. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11:6981. https://doi.org/10.3390/su11246981
23. Nielsen S (2011) Sludge treatment reed bed facilities-organic load and operation problems. Water Sci Technol 63:942–948
24. Stefanakis AI, Tsihrintzis VA (2012) Effect of various design and operation parameters on performance of pilot-scale sludge drying reed beds. Ecol Eng 2012(38):65–78
25. Uggetti E, Ferrer I, Carretero J, Garcia J (2012) Performance of sludge treatment wetlands using different plant species and porous media. J Hazard Mater 217–218:263–270
26. Peruzzi E, Nielsen S, Macci C, Doni S, Iannelli R, Chiarugi M, Masciandaro G (2013) Organic matter stabilization in reed bed systems: Danish and Italian examples. Water Sci Technol 68:1888–1894
27. Stefanakis AI, Akratos CS, Melidis P, Tsihrintzis VA (2009) Surplus activated sludge dewatering in pilot-scale sludge drying reed beds. J Hazard Mater 172(2–3):1122–1130
28. Stefanakis AI, Tsihrintzis VA (2012) Heavy metal fate in pilot-scale sludge drying reed beds under various design and operation conditions. J Hazard Mater 213–214:393–405
29. Peruzzi E, Macci C, Doni S, Iannelli R, Masciandaro G (2017) Stabilization process in reed bed systems for sludge treatment. Ecol Eng 102:381–389
30. Koottatep T, Surinkul N, Polprasert C, Kamal ASM, Kone D, Montangero A, Heinss U, Strauss M (2005) Treatment of septage in CWs in tropical climate: lessons learnt after seven years of operation. Water Sci Technol 51(9):119–126
31. Kengne IM, Akoa A, Kone D (2009) Recovery of biosolids from constructed wetlands used for faecal sludge dewatering in tropical regions. Environ Sci Technol 43:6816–6821

32. Hu S, She X, Wei X, Hu B, Hu C, Qian Y, Fang Y, Zhang X, Bashir S, Chen Z (2017) Surplus sludge treatment in two sludge treatment beds under subtropical condition in China. Int Biodeter Biodegrad 119:377–386
33. Stefanakis AI (2018) Constructed wetlands for industrial wastewater treatment, 1st edn. Wiley, Chichester
34. Langergraber G, Dotro G, Nivala J, Rizzo A, Stein OR (2019) Wetland technology: practical information on the design and application of treatment wetlands, 1st edn. IWA Publishing, London, UK
35. Nielsen S (2003) Sludge drying reed beds. Water Sci Technol 48:101–108
36. Nielsen S, Peruzzi E, Macci C, Doni S, Masciandaro G (2014) Stabilisation and mineralisation of sludge in reed bed systems after 10–20 years of operation. Water Sci Technol 69:539–545
37. Nielsen S (2007) Sludge treatment and drying reed bed systems. 2007. Wastewater treatment in wetlands: theoretical and practical aspects. Water Sci Technol 3-4:223–234
38. Nielsen S (2007) Helsinge sludge reed bed system: reduction of pathogenic microorganisms. Water Sci Technol 56:175–182
39. Baawain MS, Mohsin AJ, Choudri BS (2015) Characterization of industrial wastewater sludge in Oman from three different regions and recommendations for alternate reuse applications. Iran J Public Health 44(11):1473
40. Baawain MS, Mohsin AJ, Choudri BS (2014) Characterization of domestic wastewater sludge in Oman from three different regions and recommendations for alternative reuse applications. Iran J Public Health 43(2):168
41. Al-Busaidi A, Ahmed M, Shaharoona B (2017) Evaluating continuous application of treated sludge on soil and plant productivity. J Agric Marine Sci [JAMS] 22(1):2–7
42. Stefanakis AI, Tsihrintzis VA (2011) Dewatering mechanisms in pilot-scale sludge drying reed beds: effect of design and operational parameters. Chem Eng 172(1):430–443
43. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
44. ACC Project (2020) Course manuals 2018: how treatment technologies impact the climate: overview. Lesson 15: sludge treatment in Jordan. http://www.dwm-acc-jordan.net/fileadmin/Library/How_Treatment_Impacts_the_Climate/Module5_L15-17_online.pdf. Accessed 8 Mar 2020
45. Alwahaibi B, Jafary T, Al-Mamun A, Baawain MS, Aghbashio M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. https://doi.org/10.1016/j.jclepro.2021.126558
46. Nielsen S (2019) Sludge treatment reed bed technology under hot and arid climate. In: Proceedings of the 8th international symposium on wetland pollutant dynamics and control (WETPOL), Aarhus, Denmark, 17–21 June 2019

Chapter 16
Full-Scale Experiences of Arid and Semi-Arid Land-Based Decentralized Constructed Wetlands in India and China

Meera Keraliya, Nitin Kumar Singh, Manish Yadav, Hirendrasinh Padhiyar, and Arti Thanki

Abstract Water stress is a perennial concern in developing as well as developed countries, which ultimately affects the water and nutrient budget of emerging economies. In this context, both India and China are reported to have wide experiences of constructed wetlands (CWs) for wastewater treatment, especially in their arid and semi-arid regions. One of the crucial factors in adapting these systems is its high evapotranspiration rates. To minimize the water losses through evapotranspiration in arid/semi-arid region oriented CWs, attention is mostly paid to potential plant species and suitable treatment configurations. To date, various configurations of CWs such as horizontal flow, vertical flow, free water surface, subsurface, and hybrid ones have been reported very effective in Asian regions. With regard to plant species, macrophytes such as *Cyperus alternifolius*, *Nasturtium officinale, Cardamine pratensis, Canna generalis* etc. have been emerged for the treatment of municipal and industrial effluents in arid regions. Recent research reports revealed that CWs, based on these species, have a significant potential of dealing with conventional (organics, nitrogen, phosphorus, heavy metals) and emerging pollutants (pharmaceuticals and personal care products, radioactive waste, petroleum hydrocarbons, dyes, and toxic phenolic compounds). Various functional mechanisms involved in pollutants removal are discussed in this chapter. Besides, the role of climatic factors and sustainability aspects are also reviewed in this chapter. Overall, this chapter shed light on various full scale CWs in Asian countries, with major

M. Keraliya · N. K. Singh (✉) · H. Padhiyar · A. Thanki
Department of Environmental Science and Engineering, Marwadi University, Rajkot, Gujarat, India
e-mail: meeraben.keraliya105867@marwadiuniversity.ac.in; nitinkumar.singh@marwadieducation.edu.in; hirendrasinh.padhiyar@marwadieducation.edu.in; arti.thanki105866@marwadiuniversity.ac.in

M. Yadav
Central Mine Planning and Design Institute Limited, Bhubaneswar, India
e-mail: manish.yadav@coalindia.in

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_16

emphasis on emerging macrophytes applied, treatment configurations, performance analysis, and mechanistic factors of CWs in arid/semi-arid climates.

Keywords Arid and semi-arid regions · Constructed wetlands · Treatment configurations · Emerging macrophytes · India · China

16.1 Introduction

Around 30–40% of the earth's terrestrial land surface is occupied by arid regions, and the biggest challenge of such areas is scarcity of water [1]. Further, ensuring water availability in arid and/or semi-arid regions is one of the most limiting factors of sustainable development. These regions are also reported to face increasing occurrence of summer droughts, as a result of global warming [2]. These issues ultimately force the society and researchers to maximize the reuse of treated wastewater for their potable and/or non-potable uses. Such hurdles become more problematic in densely populated regions such as India and China. Rapid growth in urbanization and population has also caused significant increase in discharge of wastewater from developing countries such as India and China [3].

Among various decentralized treatment technologies of these countries, constructed wetland (CWs) is one of the low-cost (operation and maintenance) engineered systems, which have been proven suitable for wide range of point and non-point sources of wastewaters. This engineered treatment system basically works on the combination of various biological (aerobic, anoxic, and anaerobic), and physicochemical processes such as filtration, adsorption etc. These processes are mainly facilitated through some filter media, also known as permeable substrate (gravel, sand, rock, or soil etc.), and vegetative cover or plants, particularly capable of utilizing the wastewater pollutants for their growth [4]. At regular intervals, the plants are harvested and may be utilized for specific resource recovery/production such as biodiesel [5, 6]. The role of the used substrate/filter media is to remove the wastewater pollutants through physical processes such as sedimentation, adsorption, and entrapment etc. as well as to provide a support for the growth of vegetative cover in CWs [7]. As reported in previous literature, the flow provision/direction for wastewater may be made either over the surface or through the substrate, followed by a treated water collection system, water level control mechanism, or inlet-outlet arrangement. Further, considering the groundwater quality management, a suitable liner may also be used to ensure the field sustainability of CWs. Having these design considerations in mind, various configurations of CWs, based on the type of macrophytes used (free floating, submerged or emergent), wastewater flow patterns (horizontal flow, vertical flow, free surface, or sub surface etc.), or single/multi stage have been suggested by worldwide researchers for developing as well as developed countries [4].

With reference to arid and semi-arid regions, some specific challenges such as ecological deterioration, increased water loss rate, environmental factors, soil

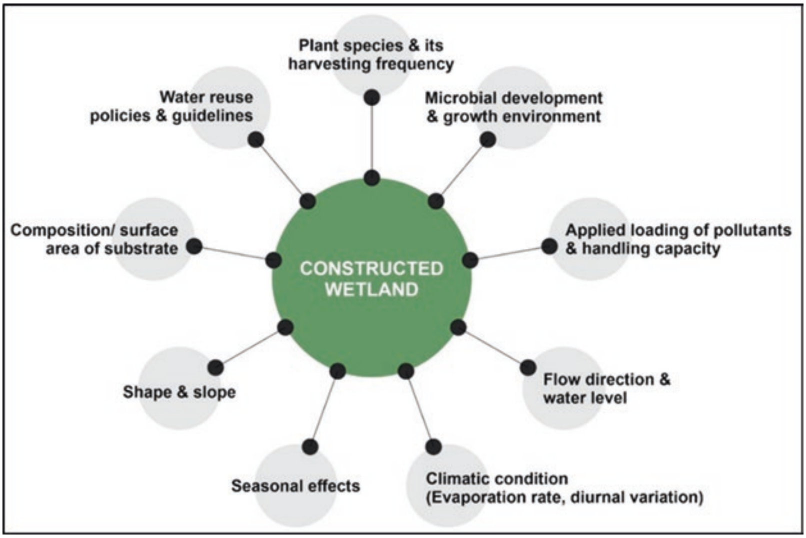


Fig. 16.1 Typical design elements of CWs, with special emphasis on arid and/or semi arid regions

salinization, insufficient precipitation, and increased evapotranspiration (increased dissolved concentration) etc. may hinder the successful establishment CWs in India and China [8]. These concerns and limitations clearly revealed that CWs may behave differently than their counterparts, established in more mesic and humid regions [9]. More specifically, in summer and spring season of these regions, high evapotranspiration rate reduces the outflow rate significantly, causing an increase in hydraulic retention time, concentration of non-biodegradable pollutants, and soil salinity for irrigation reuse areas [2, 10–13]. The negative aspects of CWs in arid and semi-arid regions may also be noticed through regular monitoring of Na concentration, electrical conductivity, and sodium absorption ratio in influent and effluent, revealing almost similar values [14]. Having these constraints in mind, the selection of suitable, efficient, and effective plant species plays a critical role in enhancing the treatment performance of CWs in a sustainable manner. Figure 16.1 shows the typical design elements of CWs in arid and semi-arid regions.

16.2 Constructed Wetland – A Decentralized Solution for Arid/Semi-Arid Regions

A decentralized wastewater treatment system is a more sustainable option for small towns, rural communities, and peri-urban areas of developing countries. These systems are being rapidly established worldwide over the last few decades, as an alternative of conventional and technically complex wastewater treatment systems [15]. In this context, like other decentralized wastewater treatment technologies, CWs

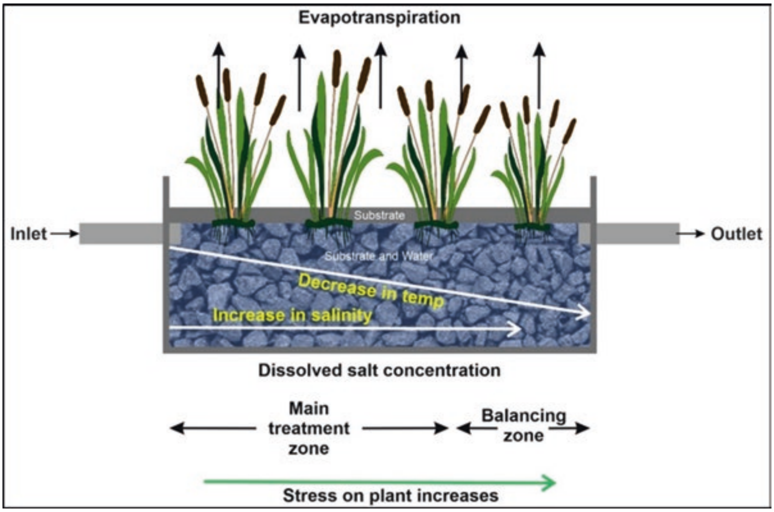


Fig. 16.2 Arid and semi-arid scenario for Constructed wetland

have also been well established across the globe, and can be applied in a wide range of settings, wastewaters, pollutants types, and atmospheric conditions, i.e., from arid to tropical. Nowadays, due to versatility, ecological benefits, land conservation, and usability in touristic facilities, CWs are gaining significant acceptance by researchers, scientists, and stakeholders of emerging economies such as China and India [5]. The water temperature in arid and semi-arid land based CWs is of main interest for three reasons: rate of change in biological processes, equilibrium shift in selective water quality parameters, and evaporative losses [16]. Another limitation, associated with operation of CWs in arid regions, is low biomass production of plant species. However, few researchers have also reported the higher biomass yield in such regions [11, 12]. Thus, such conditions lower down the overall output of these CWs with reduced supply of effluent for reuse [17, 13]. Figure 16.2 depicts the typical scenario of CWs for arid/semi-arid regions.

The below sections provide information about various treatment configurations of CWs, emerging macrophytes, and functional mechanisms involved in the treatment of various types of wastewaters.

16.2.1 Treatment Configurations and Investigated Wastewaters

To date, various configurations of CWs have been applied at lab and field scale in Indian and Chinese arid and semi-arid regions. Most of the available CWs can be broadly classified in three categories as follows: traditional, hybrid, and enhanced [18–21]. Figure 16.3 summarizes the various types of CWs which have been applied in different settings of India and China.

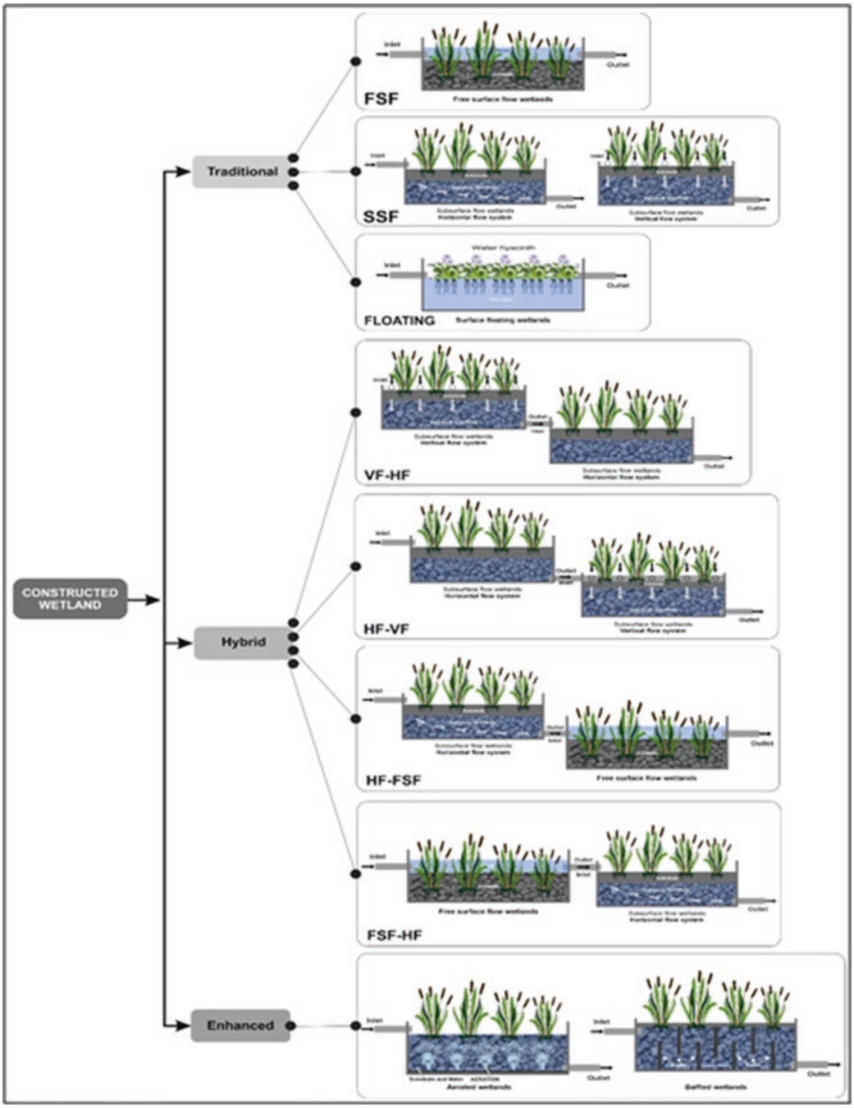


Fig. 16.3 Various configurations of Constructed wetlands in different settings of India and China

Among these, traditional CWs cover free surface flow, subsurface flow (horizontal flow and vertical flow), and floating wetlands. Hybrid CWs are simply combinations of two or more types of CWs such as horizontal followed by vertical flow, vertical flow followed by horizontal flow, or any combination of other types of CWs. The enhanced CWs may include external aeration or baffled flow arrangement. Such strategies mainly contribute to oxygen availability, subsequently to increased pollutant removal efficiencies in CWs. Besides, the performance of enhanced CWs can also be increased by suitable pre- or post- treatment strategies [22–24].

With reference to wastewater types, CWs have been increasingly extended to treat a wide range of wastewater sources from domestic, greywater, black water, acid mine drainage, agricultural wastewater, industrial wastewater, and landfill leachate [12, 25–27], which can be reusable for different purposes. The arid and semi-arid based systems are also emerging solutions of rural communities and sparsely populated regions [24–29].

16.2.2 Emerging Macrophytes of India and China – An Overview

Across the world, macrophytes are an important part of every CW, covering all types of climate and regions as well. Their requirement is well justified as they have unique role in ensuring the sustainability of existing and upcoming CWs [30]. In particular, macrophytes provide stability to the CW structure, offer diversified conditions for the removal of various organic and inorganic pollutants, cope up with hydraulic and organic shock loads, minimize substrate surface freezing in winter, and provide high surface areas for microbial and physicochemical processes [31]. With these capabilities, CWs are also expected to withstand the adverse environmental conditions of arid and semi-arid regions of India and China. In spite of these benefits, the selection of an appropriate CW plant in arid regions is still challenging, and is based on its environmental requirements, climatic conditions, types of wastewater to be treated, pollutant's loading, landscape impact of wetlands etc. [31].

Further, to improve the growth, productivity, and performance of plants there are several management strategies which can be applicable. Such examples include annual or multiple harvesting. Rather than mature wetlands, newly planted plants will take up more nutrients (nitrogen, phosphorus, etc.) which will later leach from the withered plants along with the uptake by growing plants. It is important to mention here that frequent plant harvesting can cause a slowdown in growth, therefore annual harvesting or harvesting at the end of the growing season promotes the uptake of more nutrients by new plants [23, 32]. To date, the major constraints in ensuring the sustainability of CWs is the capability to effectively grow suitable macrophytes on which functional mechanisms are mainly dependent. Table 16.1 lists the various emergent macrophytes which have been successfully applied for small and/or large scale CWs, treating various types of wastewaters in arid or semi-arid regions of India and China. The macrophytes, shown in Table 16.1, are reported for appreciable uptake of nitrogen and phosphorus forms, organic, inorganic matter, solids, or heavy metals, which are well known drivers for the growth of the plants and microbial population.

As reported in Table 16.1, most of the macrophytes are used for municipal sewage, grey water, secondary effluents of biological treatment systems, and some

Table 16.1 Emerging macrophytes used in CWs of arid and semi-arid regions in India and China

Species	Name of species	Family	Treated wastewater	Country	References
	*Phragmites australis*	*Poaceae*	Oilfield process waters, greywater, sewage, secondary effluents	China, India	[8, 28, 29, 33, 34]
	*Canna indica*	*Cannaceae*	Grey water, domestic wastewater	China, India	[23, 24, 34, 35]

(continued)

Table 16.1 (continued)

Species	Name of species	Family	Treated wastewater	Country	References
	*Typha latifolia*	*Typhaceae*	Pb/Zn mine water, sewage	China, India	[29, 33, 35]
	*Pistia stratiotes*	*Araceae*	Sewage	China, India	[29, 35]
	*Lemna minor*	*Lemnaceae*	Secondary effluents	China	[28]

	*Typha orientalis*	*Typhaceae*	Secondary effluent	China, India	[28]
	*Polygonum hydropiper*	*Polygonaceae*	Sewage	China	[29]
	*Canna flaccida*	*Cannaceae*	Greywater	China, India	[34]

(continued)

Table 16.1 (continued)

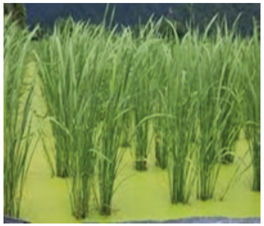
Species	Name of species	Family	Treated wastewater	Country	References
	*Acorus calamus*	*Acoraceae*	Domestic wastewater	China	[23]
	*Ageratum conyzoides*	*Asteraceae*	Domestic wastewater	India	[35]
	*Alternanthera sessilis*	*Amaranthaceae*	Sewage	China	[29]

	*Cardamine pratensis*	*Brassicaceae*	Greywater	India	[34]
	*Nelumbo nucifera*	*Nelumbonaceae*	Secondary effluent	China	[28]
	*Colocasia esculenta*	*Araceae*	Sewage	China	[29]

(continued)

Table 16.1 (continued)

Species	Name of species	Family	Treated wastewater	Country	References
	*Nymphaea tetragona*	*Nymphaeaceae*	Secondary effluent	China	[28]
	*Crossandra infundibuliformis*	*Acanthaceae*	Greywater	India	[34]
	*Plectranthus amboinicus*	*Lamiaceae*	Greywater	India	[34]

	*Solanum trilobatum*	*Solanaceae*	Greywater	India	[34]
	*Potamogeton crispus*	*Potamogetonaceae*	Secondary effluent	China	[28]
	*Zizania latifolia*	*Poaceae*	Secondary effluent	China	[28]

(continued)

Table 16.1 (continued)

Species	Name of species	Family	Treated wastewater	Country	References
	*Water hyacinth/ Eichhrinia crassipes*	*Pontederiaceae*	Secondary effluent	China	[28]
	*Zizania caduciflora*	*Poaceae*	Municipal sewage	China	[33]
	*Lolium perenne*	*Poaceae*	Refinery wastewater	China	[36]

	*Geophila herbacea O Kumtze*	*Rubiaceae*	Refinery wastewater	China	[36]
	*Canna generalis*	*Cannaceae*	Municipal sewage	China, India	[36]

specific wastewaters. These macrophytes are reported to have high resistance to saline conditions, expected to occur due to high evapotranspiration rates, while optimizing contaminant's removals [37].

16.2.3 Functional Mechanisms Involved in Pollutant's Removal

The removal of wastewater pollutants often relies on the diverse range of co-existing physico-chemical, biological processes, or combination of these processes [38]. Further, the efficiency of these processes is vitally dependent on various other environmental factors and operational parameters [39]. Among various types of pollutants, most of the pollutants are categorized in following categories: organics, inorganics, solid, nutrients, and other toxic pollutants such as metal, pesticides, and industry specific chemicals. The mechanisms involved in the removal of these pollutants may differ from each other, depending on the operational factors and other environmental conditions [40]. Table 16.2 lists the various mechanisms involved in the removal of various pollutants.

Figure 16.4 shows the various mechanisms, which are possibly involved in nitrogen, pathogen, organics and phosphorus removal in CWs in arid and semi-arid regions.

These functional processes are also affected by other parameters such as pH, temperature, oxygen and carbon source availability, feeding strategies, operational inputs, and redox conditions. Besides, the major operational and climatic conditions also play an important role in defining the functional phenomenon of treatment. Below are details of various mechanisms which are mainly involved in pollutant

Table 16.2 Major treatment processes and corresponding target pollutant's removal in CWs [38, 41–43].

Types and processes		Major pollutants removed
Physical	Sedimentation; filtration; adsorption; volatilization; flocculation; precipitation; transpiration; absorption etc.	Suspended solids, biodegradable organics, phosphorus, microbial contaminants, various forms of nitrogen
Chemical	Photochemical oxidation; Hydrolysis; oxidation/reduction; Photolysis; Cation/anion exchange	Phosphorus, organics, heavy metals, various forms of nitrogen etc.
Microbial assisted process	Nitrification; denitrification Bacterial metabolism; biodegradation; mineralization; assimilation	Biodegradable organics, various forms of nitrogen, faecal contaminants, phosphorus etc.
Plant assisted process	Plant metabolism; bioaccumulation; growth and uptake; Phytoaccumulation; Phytovolatilization; Phytoextraction; Rhizo-filtration	Faecal contamination, metals, nitrogen and phosphorus forms etc.

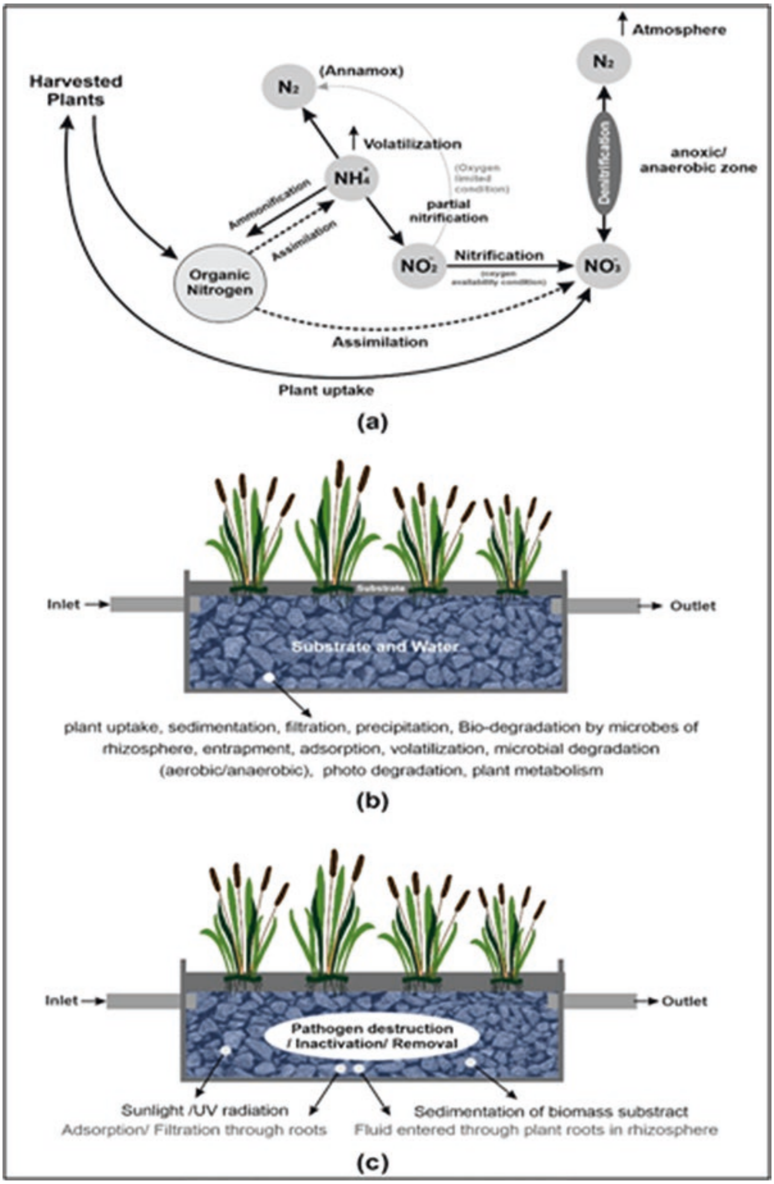


Fig. 16.4 Functional mechanisms typically involved in nitrogen, pathogen removal, and other pollutants removal in CWs

removals in CWs. With reference to nitrogen removal and transformation in CWs, as well as disappearance of all forms of nitrogen, i.e., ammonia nitrogen (NH_4^+), nitrite and nitrate nitrogen (NO_2^- & NO_3^-), organic nitrogen etc., Fig. 16.4a shows that, along with conventional nitrification and denitrification process, the conversion of nitrogen through annamox process is also reported in CWs. Besides, assimilation and volatilization process also contribute to the overall nitrogen removal [39].

Other pollutants such as organics, phosphorus, metals, and inorganics are typically removed by various mechanisms, as shown in Fig. 16.4b. The details of these mechanisms are well reported in previous studies. Literature review revealed that CWs are also very effective in removing pathogens from municipal and industrial wastewaters. The mechanisms involved in deactivation/removal/destruction of pathogenic microorganisms include solar irradiation, sedimentation on substrate, adsorption, or filtration through roots (Fig. 16.4c) [44]. With reference to arid and semi-arid regions, high temperature and solar irradiation with low humid conditions may also be helpful in inactivation of harmful microorganisms. *Shingare* et al. [30] and *Wu* et al. [21] reported that diversified design of CWs can achieve a removal of 4–5 log reduction.

16.3 Performance Analysis of Point and Non-point Sources of Wastewater

The treatment mechanisms in CWs are same for both point source and non-point sources of wastewater. In general, the performance of CWs depends on many operating conditions including flow path, temperature, and type of vegetation grown over the substrate. Among these factors, flow path is reported to be the most influencing one when compared with other operating conditions of CWs. Temperature is second most influential factor and it has been observed that at high temperature zones, a significant removal of wide range of pollutants can be expected [45], while a minimal effect has been reported due to the presence of different types of vegetation in CWs. It is important to mention here that the application of vegetation is mostly reported to be linked with enhanced nitrogen and phosphorus removal. The performance of CWs for the removal of major pollutants types are discussed in the below subsections.

16.3.1 Organics and Solids Removal

The mean removal efficiencies of major organics associated parameters, i.e., biological oxygen demand, BOD; and chemical oxygen demand, COD, and total suspended solids (TSS) are mainly reported high in summer season followed by a decreasing trend in winter and spring season [16, 19, 24]. In a study, the removal efficiency for TSS was 62 ± 18% in summer, and 34 ± 34% in winter, similarly for BOD it was 41 ± 10% in summer, and 23 ± 15% in spring seasons [24]. In the same study, the overall removal efficiency for a period of 22 months was TSS, 53%;

BOD, 37% and COD, 32%; respectively [24]. Such varied efficiencies are also reported to be associated with solar radiation and ambient temperature, as these factors affect the performance of wetland on daily as well as on seasonal basis. Overall, with respect to organics removal, it has been observed that higher temperature favors higher efficiency of organics and solids, and vice-versa. In another study [46] from India, in which vertical flow CW was used with *Canna indica* and *Acorus calamus* combination of vegetation, the removal efficiency was 81.79% and 78.74% for BOD through *Canna indica* and *Acorus calamus* wetlands; respectively. Whereas, total dissolved solids (TDS) removal efficiency reported with *Canna indica* planted wetland as 22.31%, and in *Acorus calamus* planted wetland as 18.96%. The growth of plants is observed to be directly linked with the removal efficiency of TDS. Improvement in removal of TDS can be seen when sedimentation occurs, and microbial activity takes place at the plant roots for assimilation of TDS [46].

16.3.2 Nitrogen Removal

The typical nitrogen removal mechanisms in CWs include volatilization, ammonification, nitrification, denitrification and plant uptake matrix adsorption [25]. A large number of physical, chemical and biological transfer processes connect all these mechanisms. Besides, redox conditions are also provided by CWs which is inevitably required for nitrification and denitrification processes. In case where organics are present, the horizontal flow CW is reported to be suitable for denitrification, which may be associated with saturation of the filtration bed [47, 48], whereas, intermittently fed vertical flow CW mainly provide aerobic conditions. In free water surface CWs, the nitrification takes place due to the oxygen availability, which is supplied by submerged plants, cyanobacteria and photosynthesis of algae, while denitrification occurs at the bottom layer of substrate. Moreover, ammonia volatilization generally take place at high pH values, when photosynthetic activity of submerged plants and macrophytes is usually high [33].

In many studies it has been confirmed that CWs play vital role in NH_4-N removal. In a hybrid CWs, the removal efficiency of NH_4-N in vertical flow beds was 56%, while in horizontal flow beds it was limited to 29% [47]. With reference to potentiality of macrophytes for nitrogen removal, *Cannabis indica, Vetiveria zizanioides, Schoenoplectus lacustris, Iris pseudacorus*, have absorbed the most nitrogen from the water [22, 33]. In a study, *Iris pseudacorus* has absorbed only 70.5% while *Vetiveria zizanioides* has absorbed 90.2% of TN in the third test phase [33, 39]. In another study conducted by Yu et al. [48], TN removed by CW was 8834.32 g, out of which 1670.66 g was removed by substrate adsorption, and 67.99 g was removed by plant uptake. The possible nitrogen removal mechanism was in the order of: nitrification- denitrification (80.32%) > substrate adsorption (18.91%) > plant uptake (0.77%) [48].

16.3.3 Phosphorus Removal

Primary mechanism by which phosphorous removal occurs in most of the CW types is adsorption, and soluble form of phosphate can only be absorbed by plants. Besides, a number of microbes, present in the soil, are also responsible for the conversion of insoluble phosphate into soluble form [7, 32]. But during higher loading rates when wastewater starts flowing on the surface, adsorption can no longer play a role in phosphorous removal. Phosphorous removal by other processes such as soil accretion, precipitation, plant uptake and microbial uptake becomes negligible in subsurface flow wetlands. The mechanism of phosphorus removal was observed to be similar as nitrogen following these observations: (1) the longer the run time, the higher the phosphorus removal, (2) once the plant reached the maturity stage, the removal of phosphorus became independent of species grown in CW, (3) a negative correlation was observed between hydraulic retention time and phosphorus removal.

In a study conducted by Yu et al. [48] in which *Vetiveria zizanioides, Cannabis indica, and Iris pseudacorus* species were used to check their efficiency in phosphorus removal, it was found that the highest removal efficiency in the second water retention time is 85.2% for *Vetiveria zizanioides,* 81.5% for *Cannabis indica*, and 81.5% for *Iris pseudacorus* respectively.

16.3.4 Heavy Metal Removal

Heavy metals in wastewater are common concern of environmental pollution, mainly due to its toxicity. Due to the high toxicity level of heavy metals there is a common goal to keep rivers and ocean safe from being polluted by heavy metals. CWs have shown significant potential to remove heavy metals from various wastewaters. A study conducted by Leung et al. [49] at Shaoguan wetland in China shows 99% removal of heavy metals such as Pb, Zn, Cu and Cd. The total accumulation of Cd, Cu, Pb, and Zn in the effluent were 4302 (g/year), 57,981 (g/year), 710, 208 (g/year) and 1,945,294 (g/year), respectively. As compared to inlet loadings, the metals mass balance at the outlet represents less than 1% of the initial mass inputs. On average, 99.9% of metals are adsorbed by the sediments, and a very small part of metals is taken up by the plants used in the wetlands [49].

In a study conducted on arsenic removal, it was reported that vegetation of CW (*Eleocharis macrostachya*) plays a vital role in the arsenic accumulation capability [50]. Though a major role in arsenic removal is that of soil, it has been found that a CW system having combination of vegetation, soil and microbes under oxidizing conditions provides higher removal of arsenic (87–90%). Arsenic distribution can be better analyzed in the different parts of the CW system through the mass balance approach, which also inform about the accumulation of arsenic at different parts of the CW [50]. From the above observations, it can be concluded that for heavy metal removal, CWs are efficient, and most of removal occurs in the soil, while the role of plants is less significant.

16.4 Operational Parameters of Relevance for CWs

The performance of CWs for the removal of targeted pollutants is governed by the design as well as operational parameters. The design of a CWs is typically carried out using the black box concept, and reduced treatment efficiency may occur if the CWs are established without considering the influence of these parameters. Further, in view of the many connections between design parameters, operational inputs, and pollutant removal processes, it is necessary to identify the critical parameters for efficient and successful establishment of CWs [51]. Among the various operational and/or design parameters, the following can be considered relevant especially in arid and/or semi-arid regions: hydraulic residence time, water level, organic and hydraulic loadings, influent feeding strategy, plant density and harvesting frequency etc. [42, 52]. Table 16.3 shows the typical design considerations for the CWs in developing countries. Typically used support material i.e. substrates are also mentioned in Table 16.3.

The hydraulic and organic load refers to the magnitude of forces exerted in CW influencing the opportunity of the contaminants to contact the substrate, plants, and microbial communities. At high hydraulic and organic loading rates, the applied

Table 16.3 Basic design and/or operational considerations for CWs in arid/semi-arid regions, applied for wastewater treatment

General	
Parameter	Typical values[a]
Surface area (m^2/per person)	1–10
L:W ratio	2:1–5:1
Water level (m)	0.3–2.5
Slope (%)	0.5–1
Hydraulic loading rate ($m^3/m^2/d$)	1–1.5
Hydraulic retention time (d)	2–30
Organic loading (g $BOD_5/m^2/d$)	10–100
Applied substrate[a]	
Natural materials	Sand, gravel, clay, marble, bentonite, dolomite, limestone, peat etc.
Industrial by products	Slag, Fly ash, alum sludge, oil palm shell etc.
Artificial products	Activated carbon, light weight aggregates, compost, calcium silicate hydrate etc.

[a]*All values can vary according to the adopted configuration of CWs (Source* [40, 53])

wastewater quickly passes through the substrate resulting in reduced contact time and increased pollutant concentrations, thus in lower CW treatment efficiencies [54, 55]. Kaur et al. [40] and Li et al. [56] observed that the performance of subsurface horizontal flow CWs was linearly affected by decreasing HLR and increasing HRT. Kaur et al. [40] reported that a hydraulic loading of 0.07 m^3/m^2/day is sufficient enough to achieve a high removal efficiency of the pollutants. Another study reported that higher organic removal rates can be achieved at higher loadings, while increase in hydraulic loading may lower the contribution of biofilms (developed on substrate) in overall pollutant removals [39, 57]. In particular, higher hydraulic loading is expected to wash away the slow growing microorganisms such as nitrifying bacteria [55]. Previous studies also reported that diffusion of oxygen is also limited in CWs, which hampers the organic matter degradation [39].

Another important parameter is the CW feeding strategy, which may considered continuous, batch, or intermittent [39]. Such strategy may influence the redox (oxidation–reduction) conditions in CW, along with oxygen availability at the remote part of the system. Among these strategies, the batch mode is reported to obtain better performance than the continuous feeding mode, through developing more oxidizing conditions. Still, it is difficult to conclude which type of feeding strategy will give a better removal of pollutants. Some studies reported that intermittent feeding can be useful in ensuring the improved organics and nitrogen removal rates in CWs [18]. Caselles-Osorio & García [58] evaluated the effect of continuous and intermittent feeding modes on contaminant removal efficiency in SSF CWs, and noted that intermittent feeding improved ammonium removal in wetland systems when compared with continuous feeding.

Critical investigation also revealed that other important parameters such as hydraulic conductivity of the substrate, plant density and harvesting frequency, oxygen level, and wastewater pH and temperature foster the necessary environment for the removal of target pollutants. Saeed & Sun [39] reported that a significant drop in pH can hinder nitrogen removal and anaerobic degradation of wastewater pollutants. The depth of water level is also a crucial factor in arid and semi-arid land based CWs. It helps in selecting the suitable species and its understanding of the evapotranspiration rate, high dissolved solids loading etc. Besides, it also plays an essential role in the rooting depth of plants. To select the depth of CW, one has to consider the appropriate hydraulic retention time as it influences the synergy between contaminants and macrophytes. Like other parameters, oxygen availability in substrate also influences the aerobic metabolic activities for the pollutant's degradation. In a CW, oxygen diffusion occurs via the following ways: influent dissolved oxygen, diffusion or convection, and oxygen release in rhizosphere by plant roots. It is important to mention here that the availability of oxygen is also linked with the water depth in CWs. Overall, it can be stated that all these parameters can either directly or indirectly impact the removal of pollutants in positive or negative manner [40].

16.5 Climatic Factors Associated with Performance of CWs

The threatening challenge, faced by arid and semi-arid land based CWs of China and India, is climate change. The net water loss in such regions is detriment, especially when water return credits are of increasing importance [59]. In practice, the treatment performance of CWs in these regions may be less consistent than others, being operated in humid, tropical, or any other region [18]. Some studies reported the best prospects for successful operation of CWs is warmer regions but arid and semi-arid lands have their own limitations. Hence, the future effectiveness of CWs in such areas is essentially dependent on the reasonable/accurate forecasting of climate change variables such as droughts, flooding, heavy precipitation, weather conditions, solar irradiation, and light intensity etc.

Along with these, water scarcity is also another concern in such regions as it increases the propensity of treated water reuse for potable or non-potable purposes [37, 13]. The high evapotranspiration rates could adversely impact the performance of CWs at a certain level [60]. In case of cold and arid places, the CWs may continue to function with decreased rate of microbial decomposition, probably due to freezing conditions [41]. Among various operational outputs e.g. treated water, harvested plants; and the quantity of biomass are also affected by climatic conditions. Werker et al. [61] reported that the efficiency of subsurface CWs may be less affected in cold arid regions for pathogen removal, as the related processes mainly take place below the surface. Various studies analyzed the effect of temperature on the performance of CWs, and reported that pathogen removal rates are directly linked with extremes in temperature and/or solar irradiation [44]. It is important to mention here that the water temperature is also linked with evapotranspiration rates of CWs [30, 40]. Furthermore, better removal of organics and nutrients may be expected in arid areas, if compared to other regions. Overall, it can be concluded that arid regions possess similar effects of climate on the performance of CWs, in terms of pathogen removal and plant uptake associated to pollutant's removals.

16.6 Sustainability Aspects and Future Perspectives

In 1987, the concept of sustainable development was introduced by Brundtland Commission, highlighting the needs of present society without compromising the requirements of future generations [62]. With this vision, the sustainability aspect of CWs in developing countries such as India and China is necessary to maximize the reuse opportunity in a circular economy (avoiding fresh water exploration) approach. Besides, CWs may be applied as a polishing step for the industrial effluents, thus promoting the sustainable industrial development [63]. Figure 16.5 shows a typical sustainability matrix for CWs in arid regions.

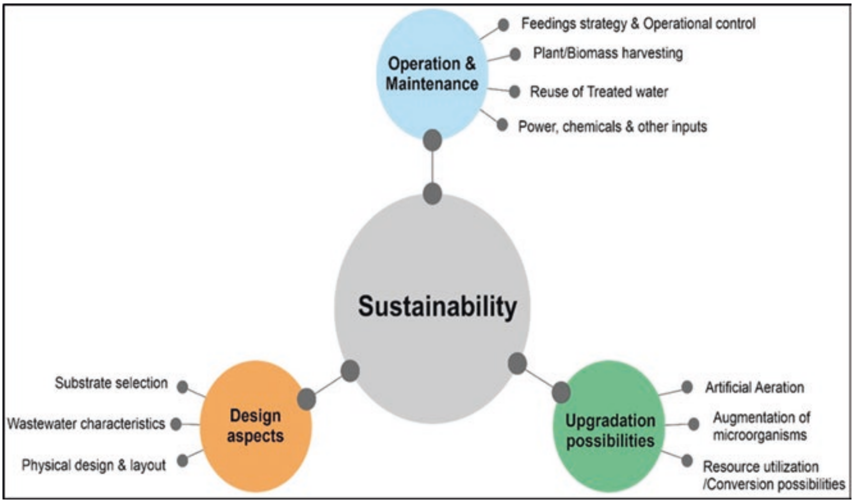


Fig. 16.5 Sustainability matrix for CWs in arid regions

In general, the sustainability of a system may be defined on three basic aspects: economic viability, treatment performance, and environmental compatibility of system. Along with these, interaction of the system and the society also plays and important role in ensuring the sustainability CWs in each climate condition. Considering the sustainable development goals of United Nations, engineered wastewater treatment systems such as CWs can contribute to the formulation of sustainable practices through their enhanced ecological carrying capacity [41]. Liu et al. [64] projected that if CWs are established as a core treatment technology throughout China, it may lead to the production of 8.2×10^7 GJ/year, which is enough to meet the requirement of two million households. Avellán & Gremillion [17] reported that the application of CWs in a nexus approach can also offset selective water supply functions. Hence, development of these systems may be considered as hallmark of sustainable cities and society.

Another important aspect which can be linked with sustainability of CWs in arid and semi-arid regions, is their ability to remove significant amounts of atmospheric carbon dioxide [65]. Nowadays, CWs are also becoming unconventional sources of water for agriculture practices, as they can provide pollutant (organics, solids, pathogens etc.) free water [13]. Hence, they can cope with increasing food security issues as well as livelihood problems [30]. Besides the aforementioned features, reduced greenhouse gases emissions also favor the establishment of CWs, when compared with other conventional and advanced treatment systems such as sequential batch reactor, membrane bioreactor, and integrated fixed film activated sludge reactors [66].

Harvesting of plants also poses another challenge in large scale CWs, as this process is labor intensive, consequently leading to increasing operational costs. Further, the timely reuse or conversion of harvested biomass for other applications i.e., bioenergy production and biofertilizers, is of special interest for worldwide researchers. It is important to mention here that the harvested biomass may also be co-digested with other organic waste to increase the bioenergy production [5, 11, 17]. Moreover, emerging operational strategies e.g. artificial aeration, step feeding, external carbon addition, microbial augmentation, use of mixed substrates, baffles flow etc. have also been reported to enhance the operational sustainability of CWs in arid regions. Overall, it can be suggested that the sustainability of CWs is mainly dependent on the medium of plant growth, type of macrophyte, and characteristics of wastewater fed to the system [18].

16.7 Conclusions

Constructed wetland works as an integrated resource recovery decentralized system to treat various wastewaters such as sewage from a small community or urban areas in developing countries. Although various potential macrophytes species are available to deal with a wide range of wastewater pollutants, the high performance of CWs in arid/semi-arid regions of India and China requires novel strategies and configurations. Further, the hot climate seems to have a positive influence in pollutant removal in some studies. In particular, hybrid CWs have showed appreciable efficiency to remove pollutants than other types of CWs. Most commonly used plants in India and China are *Typha* spp., *Canna* spp., *Pistia* spp., and P. australis. With reference to plant treatment performance, CWs have a reasonable efficiency for the removal of organics and solids having with a value of 60–70% of TSS and up to 50% removal of organics. TDS removal is also observed up to 25%. Besides, planted wetlands are also reported to be good in the removal of total phosphorous, revealing an efficiency of up to 85%. For nitrogen removal, a 56% efficiency has been reported. For heavy metals removal, up to 99% efficiency has been observed by most of the applied CWs. The selection of design and operational parameters such as plants/macrophytes, substrate/media, loading rate, water depth, retention time, and influent feed mode is observed to be critical for sustainable performance, and it must be taken into account to make them suitable for arid and semi-arid conditions. Finally, recent studies have proved that harvested wetland biomass can be used for the production of energy and bio fertilizer.

References

1. Donnelly JP, Naugle DE, Collins DP, Dugger BD, Allred BW, Tack JD, Dreitz VJ (2019) Synchronizing conservation to seasonal wetland hydrology and waterbird migration in semi-arid landscapes. Ecosphere 10(6):02758
2. Etemadi H, Samadi SZ, Sharifikia M, Smoak JM (2016) Assessment of climate change downscaling and non-stationarity on the spatial pattern of a mangrove ecosystem in an arid coastal region of southern Iran. Theor Appl Climatol 126(1–2):35–49
3. Zheng Y, Wang XC, Dzakpasu M, Ge Y, Zhao Y, Xiong J (2016) Performance of a pilot demonstration-scale hybrid constructed wetland system for on-site treatment of polluted urban river water in Northwestern China. Environ Sci Pollut Res 23(1):447–454
4. Ramprasad C, Rangabhashiyam S (2020) The role of sustainable decentralized technologies in wastewater t6reatment and reuse in subtropical Indian conditions. In: Water conservation and wastewater treatment in BRICS nations. Elsevier, pp 253–268
5. Ingrao C, Failla S, Arcidiacono C (2020) A comprehensive review of environmental and operational issues of constructed wetland systems. Curr Opin Environ Sci Health 13:35–45
6. Liu D, Zou C, Xu M (2019) Environmental, ecological, and economic benefits of biofuel production using a constructed wetland: a case study in China. Int J Environ Res Public Health 16(5):827
7. Rai UN, Upadhyay AK, Singh NK, Dwivedi S, Tripathi RD (2015) Seasonal applicability of horizontal sub-surface flow constructed wetland for trace elements and nutrient removal from urban wastes to conserve Ganga River water quality at Haridwar, India. Ecol Eng 81:115–122
8. Hu Y, Wang DZ, Zhang C, Wang ZS, Chen MH, Li Y (2013) An interval steady-state multimedia aquivalence (ISMA) model of the transport and fate of chloridion in a surface flow constructed wetland system treating oilfield wastewater in China. Ecol Eng 51:161–168
9. Sanchez CA, Childers DL, Turnbull L, Upham RF, Weller N (2016) Aridland constructed treatment wetlands II: plant mediation of surface hydrology enhances nitrogen removal. Ecol Eng 97:658–665
10. Dittrich E, Salamon-Albert É, Somfai D, Dolgos-Kovács A, Kiss T (2019) Transpiration effect of tufted sedge for a horizontal subsurface flow constructed wetland. Water Sci Technol 79(10):1905–1911
11. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
12. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. John Wiley & Sons Ltd, Chichester, UK, pp 25–42. https://doi.org/10.1002/9781119268376.ch1
13. Echchelh A, Hess T, Sakrabani R, Prigent S, Stefanakis AI (2021) Towards agroenvironmentally sustainable irrigation with treated produced water in hyper-arid environments. Agric Water Manag 243:106449. S0378377420313408 106449. https://doi.org/10.1016/j.agwat.2020.106449
14. Travis MJ, Weisbrod N, Gross A (2012) Decentralized wetland-based treatment of oil-rich farm wastewater for reuse in an arid environment. Ecol Eng 39:81–89
15. Singh NK, Kazmi AA, Starkl M (2015) A review on full-scale decentralized wastewater treatment systems: techno-economical approach. Water Sci Technol 71(4):468–478
16. El-Refaie G (2010) Temperature impact on operation and performance of Lake Manzala engineered wetland. Egypt Ain Shams Eng J 1(1):1–9
17. Avellán T, Gremillion P (2019) Constructed wetlands for resource recovery in developing countries. Renew Sust Energ Rev 99:42–57
18. Wu H, Zhang J, Ngo HH, Guo W, Hu Z, Liang S, Liu H (2015) A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. Bioresour Technol 175:594–601

19. Mustapha HI, Gupta PK, Yadav BK, van Bruggen JJA, Lens PNL (2018) Performance evaluation of duplex constructed wetlands for the treatment of diesel contaminated wastewater. Chemosphere 205:166–177
20. Srivastava P, Abbassi R, Yadav AK, Garaniya V, Kumar N, Khan SJ, Lewis T (2020) Enhanced chromium (VI) treatment in electroactive constructed wetlands: influence of conductive material. J Hazard Mater 387:121722
21. Wu S, Carvalho PN, Müller JA, Manoj VR, Dong R (2016) Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators. Sci Total Environ 541:8–22
22. Zhuang LL, Yang T, Zhang J, Li X (2019) The configuration, purification effect and mechanism of intensified constructed wetland for wastewater treatment from the aspect of nitrogen removal: a review. Bioresour Technol 293:122086
23. Pan J, Zhang H, Li W, Ke F (2012) Full-scale experiment on domestic wastewater treatment by combining artificial aeration vertical-and horizontal-flow constructed wetlands system. Water Air Soil Pollut 223(9):5673–5683
24. Patil YM, Munavalli GR (2016) Performance evaluation of an integrated on-site greywater treatment system in a tropical region. Ecol Eng 95:492–500
25. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233. https://doi.org/10.1002/elsc.201600213
26. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10(1):127. https://doi.org/10.3390/app10010127
27. Stefanakis A, Akratos CS, Tsihrintzis VA (2014) Treatment of special wastewaters in VFCWs. In: Stefanakis A, Akratos CS, Tsihrintzis VA (eds) Vertical flow constructed wetlands. Elsevier, Amsterdam, Netherlands, pp 145–164. https://doi.org/10.1016/B978-0-12-404612-2.00007-6
28. Wu H, Zhang J, Guo W, Liang S, Fan J (2018) Secondary effluent purification by a large-scale multi-stage surface-flow constructed wetland: a case study in northern China. Bioresour Technol 249:1092–1096
29. Rai UN, Tripathi RD, Singh NK, Upadhyay AK, Dwivedi S, Shukla MK et al (2013) Constructed wetland as an ecotechnological tool for pollution treatment for conservation of Ganga river. Bioresour Technol 148:535–541
30. Shingare RP, Thawale PR, Raghunathan K, Mishra A, Kumar S (2019) Constructed wetland for wastewater reuse: role and efficiency in removing enteric pathogens. J Environ Manag 246:444–461
31. Zhang T, Xu D, He F, Zhang Y, Wu Z (2012) Application of constructed wetland for water pollution control in China during 1990–2010. Ecol Eng 47:189–197
32. Zheng Y, Wang XC, Ge Y, Dzakpasu M, Zhao Y, Xiong J (2015) Effects of annual harvesting on plants growth and nutrients removal in surface-flow constructed wetlands in northwestern China. Ecol Eng 83:268–275
33. Vymazal J (2013) The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development. Water Res 47:4795–4811
34. Ramprasad C, Smith CS, Memon FA, Philip L (2017) Removal of chemical and microbial contaminants from greywater using a novel constructed wetland: GROW. Ecol Eng 106:55–65
35. Tilak AS, Wani SP, Datta A, Patil MD, Kaushal M, Reddy KR (2017) Evaluation of Ageratum conyzoides in field scale constructed wetlands (CWs) for domestic wastewater treatment. Water Sci Technol 75(10):2268–2280
36. Pavlineri N, Skoulikidis NT, Tsihrintzis VA (2017) Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. Chem Eng J 308:1120–1132
37. Nuamah LA, Li Y, Pu Y, Nwankwegu AS, Haikuo Z, Norgbey E et al (2020) Constructed wetlands, status, progress, and challenges. The need for critical operational reassessment for a cleaner productive ecosystem. J Clean Prod 122340

38. Chouinard A, Anderson BC, Wootton BC, Huang JJ (2015) Comparative study of cold-climate constructed wetland technology in Canada and northern China for water resource protection. Environ Rev 23(4):367–381
39. Saeed T, Sun G (2012) A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: dependency on environmental parameters, operating conditions and supporting media. J Environ Manag 112:429–448
40. Kaur R, Talan A, Tiwari B, Pilli S, Sellamuthu B, Tyagi RD (2020) Constructed wetlands for the removal of organic micro-pollutants. In: Current developments in biotechnology and bioengineering. Elsevier, pp 87–140
41. Zhang D, Gersberg RM, Keat TS (2009) Constructed wetlands in China. Ecol Eng 35(10):1367–1378
42. Liu T, Xu S, Lu S, Qin P, Bi B, Ding H et al (2019) A review on removal of organophosphorus pesticides in constructed wetland: performance, mechanism and influencing factors. Sci Total Environ 651:2247–2268
43. Pei H, Shao Y, Chanway CP, Hu W, Meng P, Li Z et al (2016) Bioaugmentation in a pilot-scale constructed wetland to treat domestic wastewater in summer and autumn. Environ Sci Pollut Res 23(8):7776–7785
44. Stefanakis AI, Akratos CS (2016) Removal of pathogenic bacteria in constructed wetlands: mechanisms and efficiency. In: Ansari AA, Gill SS, Gill R, Lanza G, Newman L (eds) Phytoremediation, vol 4. Springer International Publishing, Switzerland, pp 327–346. https://doi.org/10.1007/978-3-319-41811-7_17
45. Wang J, Tai Y, Man Y, Wang R, Feng X, Yang Y, Fan J, Guo JJ, Tao R, Yang Y, Chen Z, Vymazal J, Cai N (2018) Capacity of various single-stage constructed wetlands to treat domestic sewage under optimal temperature in Guangzhou City, South China. Ecol Eng 115:35–44. https://doi.org/10.1016/j.ecoleng.2018.02.008
46. Barya MP, Gupta D, Thakur TK, Shukla R, Singh G, Mishra VK (2020) Phytoremediation performance of acorus Calamus and canna indica for the treatment of primary treated domestic sewage through vertical subsurface flow constructed wetlands: a field-scale study. Water Pract Technol 15:528–539. https://doi.org/10.2166/wpt.2020.042
47. Han Z, Dong J, Shen Z, Mou R, Zhou Y, Chen X, Fu X, Yang C (2019) Nitrogen removal of anaerobically digested swine wastewater by pilot-scale tidal flow constructed wetland based on in-situ biological regeneration of zeolite. Chemosphere 217:364–373. https://doi.org/10.1016/j.chemosphere.2018.11.036
48. Yu X, König T, Qi Z, Yongsheng G (2012) Nitrogen and phosphorus removal of locally adapted plant species used in constructed wetlands in China. Water Sci Technol 66:695–703. https://doi.org/10.2166/wst.2012.200
49. Leung HM, Duzgoren-Aydin NS, Au CK, Krupanidhi S, Fung KY, Cheung KC, Wong YK, Peng XL, Ye ZH, Yung KKL, Tsui MTK (2017) Monitoring and assessment of heavy metal contamination in a constructed wetland in Shaoguan (Guangdong Province, China): bioaccumulation of Pb, Zn, Cu and Cd in aquatic and terrestrial components. Environ Sci Pollut Res Int 24:9079–9088. https://doi.org/10.1007/s11356-016-6756-4
50. Olmos-Márquez MA, Alarcón-Herrera MT, Martín-Domínguez IR (2012) Performance of Eleocharis macrostachya and its importance for arsenic retention in constructed wetlands. Environ Sci Pollut Res 19:763–771
51. Ávila C, García J (2015) Pharmaceuticals and personal care products (PPCPs) in the environment and their removal from wastewater through constructed wetlands. In: Comprehensive analytical chemistry, vol 67. Elsevier, pp 195–244
52. Masi F, Martinuzzi N (2007) Constructed wetlands for the Mediterranean countries: hybrid systems for water reuse and sustainable sanitation. Desalination 215(1–3):44–55
53. Meng P, Pei H, Hu W, Shao Y, Li Z (2014) How to increase microbial degradation in constructed wetlands: influencing factors and improvement measures. Bioresour Technol 157:316–326
54. Arivoli A, Mohanraj R, Seenivasan R (2015) Application of vertical flow constructed wetland in treatment of heavy metals from pulp and paper industry wastewater. Environ Sci Pollut Res 22(17):13336–13343

55. Yan Y, Xu J (2014) Improving winter performance of constructed wetlands for wastewater treatment in northern China: a review. Wetlands 34(2):243–253
56. Li Y, Zhu G, Ng WJ, Tan SK (2014) A review on removing pharmaceutical contaminants from wastewater by constructed wetlands: design, performance and mechanism. Sci Total Environ 468:908–932
57. Bodin H, Persson J (2012) Hydraulic performance of small free water surface constructed wetlands treating sugar factory effluent in western Kenya. Hydrol Res 43(4):476–488
58. Caselles-Osorio A, García J (2007) Impact of different feeding strategies and plant presence on the performance of shallow horizontal subsurface-flow constructed wetlands. Sci Total Environ 378(3):253–262
59. Kadlec RH (2006) Water temperature and evapotranspiration in surface flow wetlands in hot arid climate. Ecol Eng 26(4):328–340
60. Beebe DA, Castle JW, Molz FJ, Rodgers JH Jr (2014) Effects of evapotranspiration on treatment performance in constructed wetlands: experimental studies and modeling. Ecol Eng 71:394–400
61. Werker AG, Dougherty JM, McHenry JL, Van Loon WA (2002) Treatment variability for wetland wastewater treatment design in cold climates. Ecol Eng 19(1):1–11
62. Brundtland GH, Khalid M, Agnelli S, Al-Athel S, Chidzero BJNY (1987) Our common future. New York, p 8
63. Guittonny-Philippe A, Masotti V, Höhener P, Boudenne JL, Viglione J, Laffont-Schwob I (2014) Constructed wetlands to reduce metal pollution from industrial catchments in aquatic Mediterranean ecosystems: a review to overcome obstacles and suggest potential solutions. Environ Int 64:1–16
64. Liu D, Wu X, Chang J, Gu B, Min Y, Ge Y et al (2012) Constructed wetlands as biofuel production systems. Nat Clim Chang 2(3):190–194
65. Ekperusi AO, Sikoki FD, Nwachukwu EO (2019) Application of common duckweed (*Lemna minor*) in phytoremediation of chemicals in the environment: state and future perspective. Chemosphere 223:285–309
66. Benny C, Chakraborty S (2020) Continuous removals of phenol, organics, thiocyanate and nitrogen in horizontal subsurface flow constructed wetland. J Water Process Eng 33:101099

Chapter 17
Performance Assessment of Constructed Wetland in a Semi-arid Region in India Employing SWOT Analysis

Kirti Avishek and Moushumi Hazra

Abstract Constructed wetlands (CW) are man-made engineered systems that have been widely used on a global scale for the remediation of domestic wastewater, mine water, urban stormwater and industrial wastewater. Pretreatment and polishing of effluents are important and they are commonly not used as a standalone method. Considering the use of CW as a treatment technique for wastewater treatment, subsurface flow CW can be best utilized in semi-arid regions in India. The macrophytes have high growth rate that assist in high nutrient removal, resulting in effluent quality that can be used for agricultural purposes, discharged into nearby water bodies or reused for restoration and aesthetic upgrade. The treated effluent contains fecal coliform as low as 100 CFU/100 ml, making it suitable for agricultural purposes. Therefore, CW can be designed to maximize the removal of nutrients and pathogens, with diversity in plant species and substrate used and also to incorporate as a polishing unit for wastewater treatment. CW can be helpful in minimizing invertebrate predators such as mosquitoes and the potential health risk to communities residing in its vicinity. The objective of the present study is to evaluate the performance assessment of CW, with the help of SWOT matrix. SWOT analysis helps in critically reviewing the issues related to the performance, efficiency and implementation of CWs. The interpretation will lead to a deeper insight into the factors resulting in good performance, research needs, uncertainties and emerging challenges.

Keywords Constructed wetlands (CW) · Performance assessment · Wastewater · Effluents · Pollutants · SWOT analysis

K. Avishek (✉)
Department of Civil and Environmental Engineering, Birla Institute of Technology, Ranchi, Jharkhand, India
e-mail: kavishek@bitmesra.ac.in

M. Hazra
Department of Hydrology, Indian Institute of Technology, Roorkee, Uttarakhand, India

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_17

17.1 Introduction

The term water scarcity is of growing concern especially in arid and semi arid zones, where the natural resources are limited and overexploited. In a developing country like India, the challenges faced due to water scarcity are accelerated due to urbanization, population growth, increased food demand, industrialization, climate change and standards of living. India has total of 17% of world's population and only 4% of global water resources. According to the statistics, 54% of the country faces high to extremely high water stress [1]. The water scarcity/stress refers to two sides of a coin, where the major issue for water demand exceeds that of the present available resource and the poor quality of available water that restricts its uses. In addition to the above fact, the major rivers, lakes and streams, tributaries and groundwater are extracted and provide water for irrigational and industrial purposes, which account for nearly 80% of the available water used every year. As estimated by the Central Pollution Control Board of India, approximately 78% of the sewage generated in India remains untreated and the effluents are discharged to water bodies [2]. Therefore, there is a gap between sewage generation and sewage treatment, as there is lack of treatment units in urban areas. Hence, there is a need to promote the decentralized approach that focuses on water conservation, storage, reuse and source sustainability of the water that has been utilized and thrown off as waste.

Green technologies such as constructed wetlands (CW) have widely been implemented for the efficient removal of pollutants on a global scale from domestic wastewater [3], mine drainage, urban stormwater and industrial wastewater [4], such as acid uranium mine drainage or landfill leachate [5, 6], tanneries [7], effluents with hydrocarbons and phenols [8, 9, 10], and agro-industrial effluents [11, 12, 13]. A considerable amount of research has been performed at laboratory and field scale for treating wastewater loaded with inorganics, organics, nutrients, heavy metals, and for the reduction of water quality parameters. The design of CW depends on the processes that occur in any natural wetland, but in a controlled manner. Based on the flow regime, CW are generally classified into surface flow (SF or free water surface – FWS) and subsurface flow (SSF) systems [14]. The FWS CWs can be further classified according to the plant species used such as emergent, free floating, floating leaved, submerged macrophytes etc. (Fig. 17.1).

The mechanisms involved to promote metal retention and acid neutralization include formation and precipitation of metal hydroxides, metals sulfides, ion-exchange, dissolution of primary carbonate minerals, complexation of metals by organic carbon, microbially mediated sulfate reduction, and direct uptake by plant species [14–16]. CW can be either aerobic or anaerobic type depending upon the design criteria. Generally, aerobic CW use *Typha* or other plant species in a shallow structure comprising of substrate like clay, soil, mine spoils that is impermeable. The anaerobic ones have a deeper structure (>30 cm) with permeable substrate like peat, sawdust, organic compost, crushed limestone or a mix of the above. Previous studies have also reported that the performance of CW can be altered and decreased

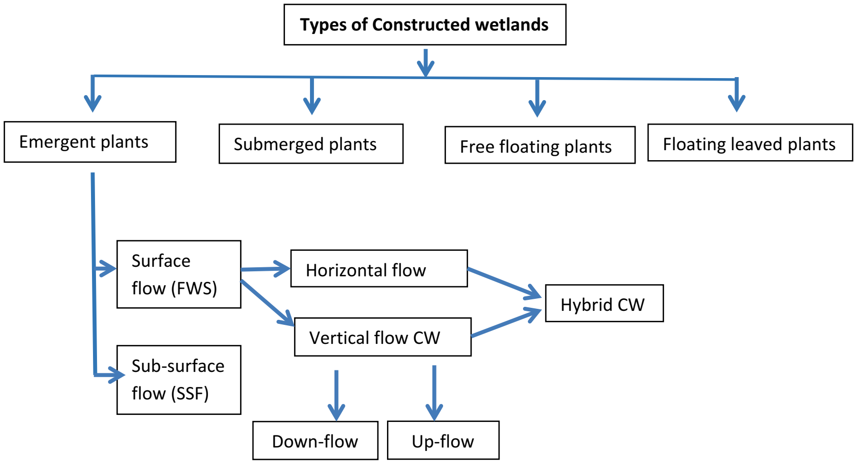


Fig. 17.1 Types of Constructed wetlands based on design parameters [6, 14]

if the influent pH is very low [17]. However, CW studies have not been used for radionucletide waste, which in the near future they may be treated through rhizofilteration in aquatic environment [18].

Pretreatment [19, 20] and polishing of effluents are important and therefore CW are not widely used as a standalone method, though nowadays there are advanced standalone designs such as the VFCW that receives raw wastewater [21–23]. Considering the use of CW as a post-treatment technique for wastewater treatment, sub-surface flow CW can be best utilized in semi-arid regions in India. The macrophytes have a high growth rate that assist in high nutrient removal, resulting in an effluent that can be used for agricultural purposes, discharged into nearby water bodies or reused for restoration and aesthetical upgrade of natural wetlands. The treated effluent contains fecal coliform as low as 100 CFU/100 ml, making it suitable for agricultural purposes [24, 25]. Therefore, CW can be designed to maximize the removal of nutrients and pathogens, with diversity in plant species and substrate used and can also be incorporated as a polishing unit for wastewater treatment. They can be helpful in minimizing invertebrate predators like mosquitoes, and potential health risk to communities residing in its vicinity [26].

17.1.1 Performance of CW in Arid and Semi-arid Regions

Previous studies have reported that halophytic plant species such as common reeds and cattails, demonstrate good removal of pollutants from domestic and agricultural wastewater [11, 14, 23, 27]. *Typha species* and *Phragmites australis* have been used as a dominant plant species in India and other countries [28–31, 13, 19, 20] with high growth rate, and greater adaptability to varying environmental conditions and wastewater type. Though, species like *Iris, Canna indica, Red Canna* have been used across India for the removal of pollutants from municipal wastewater [21, 32, 33].

Previous investigations on CW performance demonstrated the removal of suspended solids and organics, though in terms of nutrient removal (nitrogen and phosphorus) the performance is usually lower [34, 35]. The major processes involved are nitrification – denitrification and precipitation of phosphorus and adsorption to soil Ca, Al and Fe is significant [36]. The physico-chemical characteristics of the substrates and flow regimes play an important role, whereas studies have also reported the significance of hydraulic conductivity and substrate porosity. As in natural wetlands where nitrification may occur in shallow areas with coarse medium and in areas with fine sediments, denitrification may take place under saturated conditions. Most of the CW mimic natural wetlands and are therefore designed according to the need to simulate environmental heterogeneity. For this purpose, single stage or multistage hybrid CW setups are used to increase the efficiency.

CW design criteria can be optimized based on the specific needs by altering the flow pattern of water, combining different types of substrate, and types and water column depths [37]. This combination has a significant effect on nitrification, denitrification, oxidation of organic matter, or adsorption of phosphorus to the substrate. Another factor of prime significance is the particle size of the substrate used at different treatment units for alter the substrate hydraulic conductivity [38]. Simultaneously, considering the water column depth, increase in depth may alter the oxygen diffusion to deeper layers resulting in anoxic conditions, thereby promoting the development of anaerobic microbial communities. This microbial consortia assist in further degradation of pollutants in anoxic conditions. Studies have reported that the use of iron filings in addition to the substrate in vertical subsurface flow CW and inverted flow enhance the CW efficiency. Climatic conditions have a direct relation with the microbial activity and plant characteristics, especially in semi-arid and arid regions [22].

In this context, the present study deals with the use of CW as secondary and tertiary treatment in a semi arid zone of India, specifically a CW commissioned in Aligarh Muslim University (AMU), Aligarh, Uttar Pradesh. This chapter discusses the pretreatment of wastewater generated from AMU campus, and the effluent treatment with different CW configuration and types. The sludge is utilized as a fertilizer and the treated effluent is used for agricultural purposes. Furthermore, the results of the CW performance are used to compared with conventional treatment plants. In addition, the CW performance assessment is carried out with the help of SWOT matrix. SWOT analysis helps in critically reviewing the issues related to the performance, efficiency and implementation of CWs. The interpretation will lead to a deeper insight into the factors resulting in good performance, research needs, emerging challenges and uncertainties.

17.2 Methodology

For the present study, recent literature, government documents, and reports were analyzed for the current scenario of wastewater treatment, the discharge of effluent to water bodies and the potential application of CWs in semi-arid regions of India. The information was compiled to understand the challenges faced at the field level. For this, a site visit to the CW in Aligarh Muslim University, Aligarh was done. The field visit helped in understanding the CW design and configuration, and the challenges in achieving the maximum performance of the system. The present study analyzes the CW using the SWOT matrix, where previous data for the removal efficiency by specific plant species have been considered (Table 17.1). It was then sorted into four categories; strength, weaknesses, opportunities and threats. Strengths and weaknesses are considered as internal factors over which some measure of control is possible. On the other hand, opportunities and threats are considered to be external factors over which no control is possible. The type of intervention deals with the performance and efficiency of CW.

17.3 Results and Performance Evaluation

AMU has a well-developed CW (one of the eminent SWINGS Project), which treats wastewater generated from the University campus (~10,000 persons). As it was a SWINGS project, the commissioning of the CW was completed in 2016, after which it has shown good performance, without any breakdown. The wastewater discharge collected from the AMU campus, drains to the treatment site along with the discharge from nearby urban clusters. Therefore, it contains a mixture of contaminants that is homogenized before it flows to the primary treatment unit. Basically, the primary unit consists of up-flow anaerobic sludge blanket (UASB) methanogenic reactor of 50 m^3 with a hydraulic residence time (HRT) of 6 hours. The basic design path followed by sewage comprises of screens, grits, equalization tank, anaerobic digestor, feeding box and pumped from UASB to vertical siphons entering the CW. In the present case, the CW has been used for secondary treatment and assists in removing majority of the contaminants (Fig. 17.2).

The CW has a perforated pipe system, and 2 geomembrane liners to prevent groundwater contamination. The hybrid CW comprises of both horizontal (460 m^2) and vertical subsurface flow (480 m^2) CWs (HFCW, VFCW) units in parallel mode that get converged and the final effluents enters the sump. Both units have perpendicular wells for venting and allow wastewater sampling. The VFCW is planted with *Phragmites australis* and *Pharagmities karka* at a density of four plants/m^2. This unit is joined to the recirculation unit to improve the treatment efficiency of the system. Therefore, it has been designed based on the operation flexibility where the effluents can be recirculated to maximize the retention time for efficient microbial

Table 17.1 SWOT matrix for Constructed Wetlands and factors responsible for accelerating its performance

	Helpful to the objective	Harmful to the objective
Internal origin	**Strengths** Built on existing upland site Most biologically productive ecosystem, so responsible for transformation of many pollutants present in wastewater into harmless by-products Essential nutrients can be used for additional biological productivity Cost effective, easy to operate, and low-maintenance Provides habitat benefits same as that of natural wetlands Processes that help in pollutant removal are (1) microbial mediated (2) sorption (3) volatilization (4) photodegradation (5) vertical root profile which are basically solar driven processes	**Weakness** CW influenced by a variety of biological processes and biogeochemical cycles. Pretreatment and polishing of effluents are important and it is rarely used as a standalone method in India. The performance can vary according to the year, organic and hydraulic loading, weather conditions and vegetative communities. The inlet and outlet effluents can be computed based on the removal efficiency, but this has no use for design or performance prediction as it has no reflection for the basic features of the ecosystem To replicate the wetland that produces the percentage data, and to replicate the operating environmental conditions same as during the initial readings for performance is difficult
External origin	**Opportunities** Use of woody plants apart from submerged macrophytes, algae, floating vegetation, periphyton etc. For better performance interpretation, side by side studies can be conducted to study the effects of media size and type, aspect ratio, vegetation types. It has been proved experimentally that influent BOD is the labile form of organic carbon and CW can burn BOD to fuel nitrification. Biosolid dewatering wetlands are possible due to low operation and maintenance cost. Feasible for cold climates where freezing promotes dewatering of accumulated solids	**Threats** Growth, death, decay of plant biomass returns the nutrients to the CW Biogeochemical cycle imposes a seasonal cycle on many internal processes Interfacial aeration is reduced as the water surface is not exposed above the bed material Trapped total suspended solids which are generated within the wetland will accrete movable sediments/immovable soil produced from the sediments Biosolid formation at the inlet occurs due to organic loading which is maximum at the inlet Clogging is a physical process that results due to particulate deposition and could lead to overflow in the bed

contact time and the degradation capability as well as denitrification of the nitrified effluent. This also prevents clogging in the system matrix.

The HFCW serves as a polishing unit with plant species such as *Canna indica*, *Iris species* and *Sagittaria sagittifolia*, which has a good potential for lowering the water quality parameters. The treated effluent is then disinfected with solar based UV (250–280 nm) and anodic oxidation (AO) unit of 10 m^3/d capacity, and discharged to nearby agricultural fields and for irrigation of orchards, reducing this

Fig. 17.2 Constructed wetland in the campus of Aligarh Muslim University, Aligarh

way the irrigation cost for the farmers. It is also being used for aquaculture and reused for toilet flushing. The CW eliminates the problem of displeasing odors contrary to conventional treatment plants and at the same time it is aesthetically pleasing too.

There was a considerable decrease in water parameters in consideration [32]. It was found that that all the combinations of CW showed a removal efficiency of 98% for turbidity, 95% for BOD, 90% for COD, 89% for TKN, 87% for TSS and 74% for NH_4-N. The VFCW and HFCW demonstrated a varying removal trend between the treatment units. It was found that the VF performed better with respect to COD, BOD and NH_4-N removal. The COD value was reduceδ from 147 mg/L to 14 mg/L, BOD from 64 mg/L to 2.9 mg/L, NH_4-N from 34–9.9 mg/L, TKN from 39 to 3.1 mg/L, TSS from 41 to 5.4 mg/L and turbidity from 53 to 0.9 mg/L in the influent and the effluent, respectively. There was a significant increase in DO from 0.6 mg/L in the influent to 4 mg/L in the effluent. The VFCW allowed diffusion of air in the CW media bed and provided a suitable environment for nitrification [39, 40]. Since the mass loading (30 g COD/m^2/d) was less as compared to loading rates for arid and warm regions (60–70 COD/m^2/d), the system showed a better performance.

The study suggested that the system can withstand high loading rates and pathogenic contamination. With regards to coliform, it was found that the reduction was below the WHO standards, confirming that the effluent can be reused for irrigational purposes with effluent values as low as 100 CFU/100 ml [41]. Figure 17.3 presents the reduction of water quality parameters in the different units of the CW setup. One of the limitations of the present treatment system is the requirement of a large land area. It requires land for the sludge generated but with post treatment it can be used for land application. CW do not show large variations in performance except perhaps when the plant species needs to be harvested. The decay of plants is another factor that results into recirculating the nutrients back to the CW bed. Also, the formation of biosolids at the inlet entry point may reduce the efficiency of the system apart from clogging. Both internal factors (strengths and weakness) and external factors (opportunities and threats) are responsible for the performance of the CW where the former can be controlled by some measures and the latter cannot.

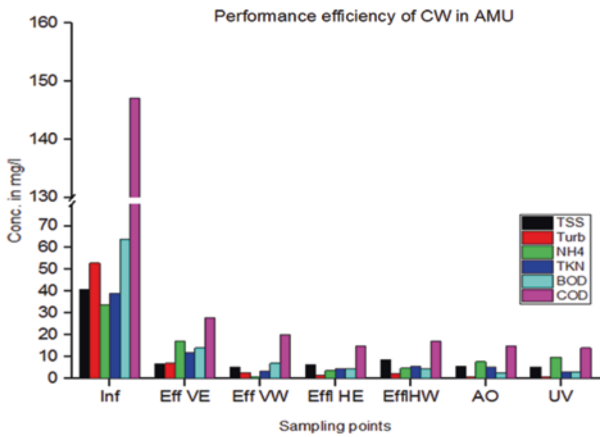


Fig. 17.3 Reduction of targeted water quality parameter in influent (inf), effluent of VFCW east (VE), effluent of VFCW west (VW), effluent of HFCW east (HE), effluent of HFCW west (HW), AO (anodic oxidation) and UV (ultraviolet)

17.4 Conclusion

CW have been applied for water security in stressed regions especially dry and semi-arid regions of India. The lack of conventional treatment and tertiary units in a developing country like India has a potential impact on the aquatic environment apart from posing the threat of water stress in most of the urban and rural areas. Moreover, wastewater treatment plants are the hotspots of pathogenic bacteria and antibiotic resistance. An interpretation from a SWOT matrix indicates that as CW mimics natural wetlands, they are biologically productive ecosystems. The degradation capacity of microbes present in the substrate and in the biofilm assists in removing the pollutants. The systems are sustainable and low cost using locally available plant species and substrates. Experimenting with woody species would help to slash the problem of dealing with the dead biomass of plant remains. Different media can be explored in a local community such as construction materials, bricks, broken marble and others.

CW can be used as an integral part in conjunction with the conventional sewage treatment plants or used directly after pre-treatment of the sewage. Therefore, incorporating CW as a treatment or polishing unit for recycling and reuse effluents free from microbial contamination, will not only benefit the society in water stressed areas but the system would also add up to the low cost and aesthetics of the surrounding environment. CW have a potential involvement in areas where decentralized communities maybe less than or equal to 10,000 person equivalent are present. The treated effluent of CW can be used for multi-purposes as integral water solution such as cleaning, gardening, toilet flushing, aquaculture, irrigational purpose, in some industries, and to safeguard the local drinking water supply. The sludge generated in the primary treatment can be used as fertilizer after post-treatment with lime. The plant species that complete their life cycle can also be harvested and be used for ornamental applications and for making nutrient-rich fertilizers. Overall, CW provide a low-cost nature-based solution to disinfection of wastewater treatment and reuse and provide optimized municipal wastewater treatment using both green and sustainable technologies.

References

1. Luo T, Young R, Reig P (2015) Aqueduct projected water stress country rankings. Technical note. World Resources Institute, Washington, D.C, pp 1–16
2. Majumder D, Maity JP, Tseng MJ, Nimje VR, Chen HR, Chen CC et al (2014) Electricity generation and wastewater treatment of oil refinery in microbial fuel cells using pseudomonas putida. Int J Mol Sci 15:16772–16786
3. Datta A, Wani SP, Patil MD, Tilak AS (2016) Field scale evaluation of seasonal wastewater treatment efficiencies of free surface-constructed wetlands in ICRISAT. India Curr Sci 110:1756–1763
4. Stefanakis AI (2018) Constructed wetlands for industrial wastewater treatment, 1st edn. Wiley, Chichester, UK

5. Rambabu K, Banat F, Pham QM, Ho S-H, Ren N-Q, Show PL (2020) Biological remediation of acid mine drainage: review of past trends and current outlook. Environ Sci Ecotechnol 2:100024
6. Vymazal J (2018) Constructed wetlands for wastewater treatment. Encycl Ecol 1:14–21. https://doi.org/10.1016/B978-0-12-409548-9.11238-2
7. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
8. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, UK, pp 25–42
9. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
10. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10(1):127. https://doi.org/10.3390/aspp10010127
11. Gomes AC, Silva L, Albuquerque A, Simões R, Stefanakis AI (2018) Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. Chemosphere 207:430–439
12. Wang M, Zhang D, Dong J, Tan SK (2018) Application of constructed wetlands for treating agricultural runoff and agro-industrial wastewater: a review. Hydrobiologia 805:1–31
13. Tatoulis T, Stefanakis A, Frontistis Z, Akratos CS, Tekerlekopoulou AG, Mantzavinos D, Vayenas DV (2017) Treatment of table olive washing water using trickling filters constructed wetlands and electrooxidation. Environ Sci Pollut Res 24(2):1085–1092. https://doi.org/10.1007/s11356-016-7058-6
14. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380(1–3):48–65
15. Maucieri C, Salvato M, Borin M (2020) Vegetation contribution on phosphorus removal in constructed wetlands. Ecol Eng 152:105853
16. Cohen RRH (2006) Use of microbes for cost reduction of metal removal from metals and mining industry waste streams. J Clean Prod 14:1146–1157
17. Mayes WM, Batty LC, Younger PL, Koiv M, Vohla C, Mander U (2009) Wetland treatment at extremes of pH: a review. Sci Total Environ 407:3944–3957
18. Eapen S, D'Souza SF (2005) Prospects of genetic engineering of plants for phytoremediation of toxic metals. Biotechnol Adv 23:97–114
19. Gaballah MS, Abdelwahab O, Barakat KM, Stefanakis AI (2022) A pilot system integrating a settling technique and a horizontal subsurface flow constructed wetland for the treatment of polluted lake water. Chemosphere 295:133844. S004565352200337X 133844. https://doi.org/10.1016/j.chemosphere.2022.133844
20. Gholipour A, Stefanakis AI (2021) A full-scale anaerobic baffled reactor and hybrid constructed wetland for university dormitory wastewater treatment and reuse in an arid and warm climate. Ecol Eng 170:106360. S0925857421002159 106360. https://doi.org/10.1016/j.ecoleng.2021.106360
21. Yadav A, Carazarenc F, Mutnuri S (2018) Development of the "French system" vertical flow constructed wetland to treat raw domestic wastewater in India. Ecol Eng 113:88–93
22. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
23. Alwahaibi B, Jafary T, Al-Mamun A, Baawain MS, Aghbashio M, Tabatabaei M, Stefanakis AI (2021) Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal. J Clean Prod 296:126558. https://doi.org/10.1016/j.jclepro.2021.126558

24. Alufasi R, Gere J, Chakauya E, Lebea P, Parawira W, Chingwaru W (2016) Mechanisms of pathogen removal by macrophytes in constructed wetlands. Environ Technol Rev 6(1):135–144
25. Gonçalves RF, de Oliveira Vaz L, Peres M, Sarnaglia Merlo S (2021) Microbiological risk from non-potable reuse of greywater treated by anaerobic filters associated to vertical constructed wetlands. J Water Proc Eng 39:101751
26. Knight RL, Walton WE, O'Meara GF, Reisen WK, Wass R (2003) Strategies for effective mosquito control in constructed treatment wetlands. Ecol Eng 21:211–232
27. Ansola G, Fernández C, de Luis E (1995) Removal of organic matter and nutrients from urban wastewater by using an experimental emergent aquatic macrophyte system. Ecol Eng 5:13–19
28. Kumar S, Nand S, Dubey D, Pratap B, Dutta V (2020) Variation in extracellular enzyme activities and their influence on the performance of surface-flow constructed wetland microcosms (CWMs). Chemosphere 251:126377
29. Kumari M, Tripathi BD (2015) Efficiency of *Phragmites australis* and *Typha latifolia* for heavy metal removal from wastewater. Ecotoxicol Environ Saf 112:80–86
30. Hejna M, Moscatelli A, Stroppa N, Onelli E, Pilu S, Baldi A, Rossi L (2020) Bioaccumulation of heavy metals from wastewater through a *Typha latifolia* and *Thelypteris palustris* phytoremediation system. Chemosphere 241:125018
31. Kraiem K, Kallali H, Wahab MA, Fra-vazquez A, Mosquera-Corral A, Jedidi N (2019) Comparative study on pilots between ANAMMOX favored conditions in a partially saturated vertical flow constructed wetland and a hybrid system for rural wastewater treatment. Sci Total Environ 670:644–653
32. Rodriguez-Hernandez MC, García De la-Cruz RF, Leyva E, Navarro-Tovar G (2017) *Typha latifolia* as potential phytoremediator of 2,4-dichlorophenol: analysis of tolerance, uptake and possible transformation processes. Chemosphere 173:190–198
33. Álvarez JA, Avila C, Otter P, Kilian R, Istenic D, Rolletschek M, Molle P, Khalil N, Amersek I, Mishra VK, Jorgensen C, Garfi A, Carvalho P, Brix H, Arias CA (2017) Constructed wetlands and solar-driven disinfection technologies for sustainable wastewater treatment and reclamation in rural India: SWINGS project. Water Sci Technol 76:1474–1489
34. Vymazal J (2010) Constructed wetlands for wastewater treatment. Water 2:530–549
35. Brix H (1994) Functions of macrophytes in constructed wetlands. Water Sci Technol 29:71–78
36. Del Toro A, Tejeda A, Zurita F (2019) Addition of corn cob in the free drainage zone of partially saturated vertical wetlands planted with *I. sibirica* for total nitrogen removal-a pilot-scale study. Water 11(10):2151
37. Stefanakis AI, Tsihrintzis VA (2012) Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands. Chem Eng J 181-182:416–430
38. Ranieri E (2003) Hydraulics of sub-superficial flow constructed wetlands in semi-arid climate conditions. Water Sci Technol 47:49–55
39. Bohórquez E, Paredes D, Arias CA (2017) Vertical flow-constructed wetlands for domestic wastewater treatment under tropical conditions: effect of different design and operational parameters. Environ Technol 38:199–208
40. Brix H, Arias CA (2005) The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: new Danish guidelines. Ecol Eng 25:491–500
41. Kulshrestha K, Khalil N (2019) Performance assessment of the vertical flow constructed wetlands treating effluent from the UASB reactor – a demonstration in a tropical climatic region. Int J Recent Technol Eng 8:9779–9781

Chapter 18
Novel Media and Unit Configurations in Advanced Constructed Wetlands: Case Studies Under Hot Climate in Thailand

Thammarat Koottatep, Tatchai Pussayanavin, and Chongrak Polprasert

Abstract At a household with limited space for installation of onsite wastewater treatment system, a new attribute for the constructed wetland (CW) systems is the multi-soil layer (MSL) system which has been developed and applied for treatment of domestic wastewaters. The CW-MSL with proper media arrangement and new-new-type multi-layer artificial wetland could achieve the desired treatment levels at the relatively small footprint, and it can be considered as advanced constructed wetland (ACW) for hot climate region. The MSL consists of permeable layers (PL) using zeolites, alternated with media mixture blocks (MBs) comprising of soil, iron particles, jute or sawdust, charcoal or alternative materials (organic residues or industrial waste). The MSL system has been found to be more efficient in treating organic matters and nutrients than other soil-based systems such as conventional CW or compact filter systems. The ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) were found to be present in the layers of MSL, which played a major role in converting ammonia to nitrogen gas. The advanced CW with tropical plant species possess the ability to break down some pharmaceutical and personal cares products (PPCPs). This ability is achieved through the Fenton reaction in which H_2O_2 generated in the plant roots reacts with iron in the soil layers to form hydroxyl radicals effective in PPCPs degradation. The ACW

T. Koottatep (✉)
Environmental Engineering and Management, Asian Institute of Technology, Bangkok, Thailand
e-mail: thamarat@ait.asia

T. Pussayanavin
Environmental Engineering and Management, Asian Institute of Technology, Bangkok, Thailand

Faculty of Science, Ramkhamhaeng University, Bangkok, Thailand

C. Polprasert
Department of Civil Engineering, Thammasat School of Engineering, Thammasat University, Bangkok, Thailand

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_18

systems could offer enormous opportunities for achieving organic matter/nutrient degradations of contaminants present in wastewater by exploiting the cooperative and mutualistic metabolisms between plants and microbial communities in both plant rhizosphere and novel media layers.

Keywords Advanced constructed wetlands · Novel media modifications · Multi-soil layer constructed wetland · Advanced oxidation process · Hot climate · Thailand

Abbreviations

ACW	Advanced constructed wetlands
AOA	Ammonia-oxidizing archaea
AOB	Ammonia-oxidizing bacteria
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
CW	Constructed wetland
MB	Mixed media blocks
mCW	Modified constructed wetland
MSL	Multi-soil layer
MSL-CW	Multi-soil layer constructed wetland
N	Nitrogen
P	Phosphorus
PL	Permeable layer
PPCPs	Pharmaceutical and personal cares products
SL	Soil layer
SMB	Soil mixture block
SS	Suspended solids
UL	Underdrain layer
VFCW	Vertical-flow constructed wetlands

18.1 Introduction of Advanced Constructed Wetlands

Constructed wetlands (CWs) are engineered wetlands with the concept of the design-based natural functions in treating wastewater. The CWs use interactions of with many ecological elements such as plats, water, media (such as soil, sand, gravel, etc.), and can naturally promote the treatment mechanisms of biological, photosynthesis and physical processes to remove organic matters, nutrients and pathogens containing in the wastewater. In hot climate regions, the CW applications are being considered as an alternative technology for wastewater treatment at the

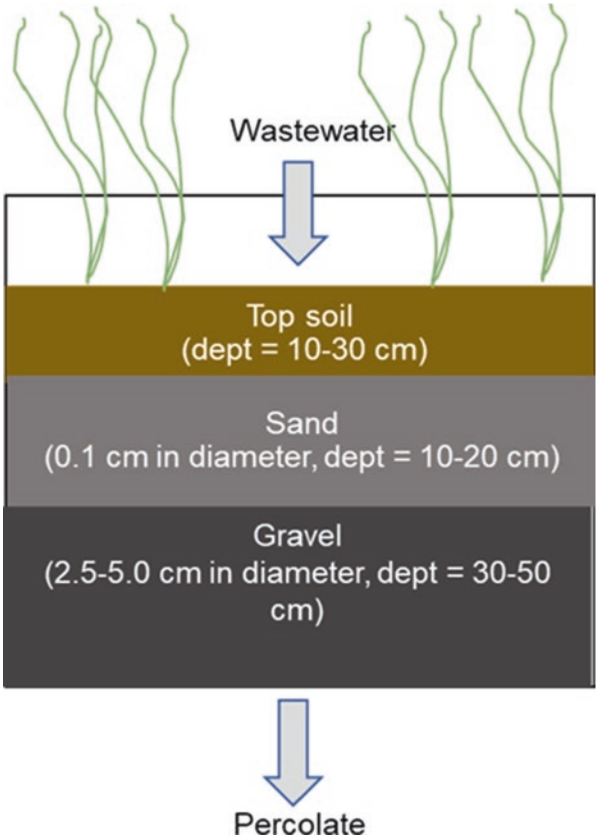


Fig. 18.1 Configuration of the VFCW

end of sewage and drainage pipeline including treatment of the effluent from on-site wastewater treatment systems. The amount of domestic wastewater generated from residential residences ranges from 100 to 600 L per capita per day with a typical average value of 260 L per capita per day. Black water generated per day is about 20–30 L per capita. The ranges of black water characteristics are found at 610–1937 mg/L of COD, 220–1416 mg/L of BOD, 10–90 mg/L of P, 230–1624 mg/L of total solid and 35–300 mg/L of TN [1–3]. The characteristics of septic tank effluent are about 100–200 mg/L of BOD, 30–63 mg/L of N and 8 mg/L of P [4]. Based on the mechanisms, the CW systems could significantly remove chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), nitrogen (N), phosphorus (P), as well as inorganics, trace organics (pharmaceuticals and personal care products, PPCPs), and pathogens present in the wastewaters.

Vertical-flow constructed wetlands (VFCW) are normally used as trickling filter or sand drying bed for wastewater treatment (Fig. 18.1). The VFCW is considered as the natural planted filter that receives the influent at the top and drains at the bottom by gravity force with the depth of the total basin varied from 50 to 100 cm. The wastewater percolates and air enters the media pores that can increase the aeration and the microbial activity. The VFCWs are uniformly fed with on surface and the wastewater flows vertically downward through the wetland media and plant's roots and rhizomes, which consist of a deeper depth of media layers of sand (10–20 cm) and gravel (30–50 cm) (underdrain layer). Emergent plants commonly used in the CWs are cattails, canna, bulrushes, padanus palms, bird of paradise, golden gingers and golden torches, etc. The main advantages of the VFCWs are low investment and O&M costs and promising treatment performance.

Advanced constructed wetlands (ACWs) or the CW with proper media arrangement and new- new-type multi-soil-layer are designed to overcome the disadvantages of the CWs. By integrating novel materials and re-design configurations, their potentials in treating wastewaters containing high contents of nutrients, pathogens and toxic compounds are expected to be improved considerably. With enhancing interactions of the media, microorganisms, and plants, the ACWs could perform better than the typical CWs of equal area. In addition, the ACW can sustain with higher hydraulic load rate (HLR) and less clogging than CW because of the larger pore volume of the media packed through the internal structure. Moreover, the ACW can be maintained and operated at a low cost and is ideal in hot climate countries for urban dense areas. Design, application, and performance of the ACW are summarized in the case studies in Sect. 18.5.

18.2 Novel Media Modifications and Modified Unit Configurations

The adsorption and precipitation processes typically take place in the ACW through chemical reactions between specific substances such as inorganic or insoluble compounds in the wastewater and CW media. The novel concept of MSL system and media configuration are applied to enhance pollutant removal process and treatability. Koottatep et al. [5] demonstrated that the application of MSL for the treatment of a septic tank effluent. The inside structure of the MSL consisted of soil layer (SL) on the top, mixed-media block (MB), permeable layer (PL) and underdrain layer (UL) (Fig. 18.2). The MB are arranged in brick-like pattern and contained with the soil, sawdust, granular iron, and biochar in different ratios depending on the wastewater type and characteristics.

Soil layer in the MSL included clay loam, marlstone and laterite soil in the top layer which serves as a habitat for microorganisms and supporting the plant growth. The fine-textured soil such as clay loam and laterite soil contain large amounts of oxidized Fe (up to 15% by weight) with the acidic range of pH about 4.4–6.6, CEC from 2 to 20 cmolc/kg and organic matters from 12 to 15 g/kg. The Fenton reactions or advanced oxidation process could occur in the CW system through the reactions between the oxidized Fe in the soil layer and hydrogen peroxide (released by plant roots) under acidic conditions, resulting in the generation the hydroxyl radicals, a strong oxidant effective in degrading complex organic compounds including PPCPs.

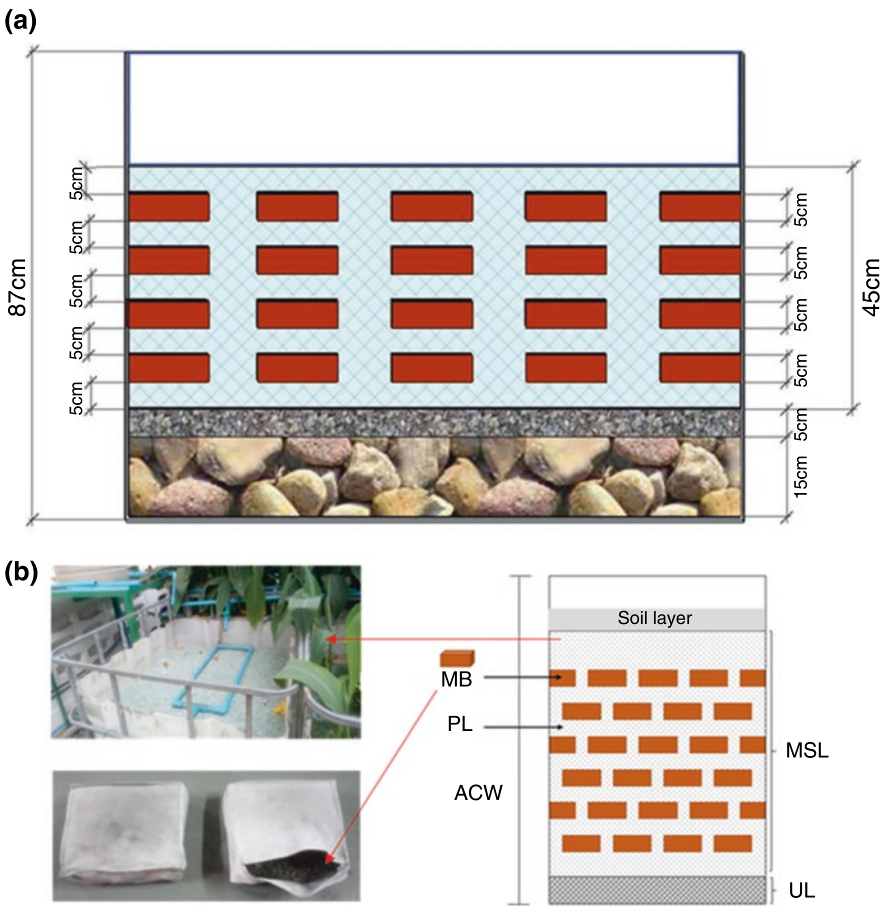


Fig. 18.2 (**a**) Inside structure of the MSL (Vertical cut with depth size), (**b**) MSL components

The MBs are arranged as bricklaying pattern and mixed with materials such as soil, sawdust, Fe rich materials, and charcoal etc. The sawdust contains a high concentration of cellulose, are effective adsorbent of pollutants, and functions as nutrients and carbon source for the microorganisms. The MBs are also additional carbon sources for microorganisms to facilitate a smooth denitrification reaction. In the MSL system, under aerobic conditions, NH_4^+-N is oxidized to NO_2^--N and NO_3^--N, which is eventually translocated to the MB to be reduced to nitrogen gas. The PL are made of activated charcoal or biochar which have high surface area and pores available for adsorption or chemical reactions. Large surface areas, high negative ions, and greater electric charge densities of these two carbon sources caused their cation capacities to be greater than other soil organic matters [6]. Therefore, the charcoal properties could help to improve the MB efficiency by increasing water retention

Table 18.1 Media composition and their roles in pollutant removals

Media type	Their characteristics
Soil (clay loam, marlstone and laterite)	Resident for plants and microorganism Adsorption Reactions from iron as a compound in laterite soil - Chemical precipitation for P removal - Fenton reaction
Sawdust	Adsorbent material - Contain a lot of cellulose, high porous and surface area Nutrient and energy sources for microorganisms in CW
Charcoal and biochar	Adsorbent material for - Organic compounds - N removal - Emerging complex compounds as PPCP or other toxic pollutants
Zeolite	- High adsorption capacity - N and P removal, etc.

and aggregation, regulating nitrogen leaching and improving microbial properties. Oxidized Fe is also effective in removing P through precipitation and in reducing emerging complex compounds as PPCP or other toxic pollutants through adsorption.

The PL also enhances the infiltration ability through its inside structure which comprises of coarse particles such as zeolite or porous stone (approximately 1–5 mm in diameter). Zeolites, aluminosilicate minerals, are normally used as adsorbents. Organic matter adheres to the surface of zeolite through physical or chemical mechanisms. Moreover, the PL should be of the steady size to decrease the risk of clogging and facilitate the dispersion of water in the system [7]. Owing to its high cation exchange capacity (CEC), the PL material has a high capacity to adsorb NH_4^+. The zeolite works not only for efficient infiltration and distribution of wastewater, but also for buffering pH change during wastewater treatment. The ULs are placed with highly porous material of gravel approximately 3–5 mm in diameter. Media type of the MSL and their characteristics are summarized in Table 18.1.

The performance of MSL system depends on the relative distribution of aerobic and anaerobic conditions along the unit depth. To balance between the anaerobic and the aerobic conditions in the MSL, aerated-MSL is therefore an optional control aspect of the system by using active or passive aeration pipes [8]. Attanandana et al. [9] found that an aeration rate of 24,000 L/m^3/day once a month could significantly increase the removal efficiencies of BOD, total N and total P from 48.2, 53.8 and 42.1% to 90.3, 90.8 and 90.1%, respectively, after providing with the aeration system.

In addition to the novel media modification, to enhance the function of the media in the CWs and MSL, the novel porous medias used were developed by mixing with the clay, laterite soil, marl, and other materials. The novel porous media could promote a path through which the wastewater passes through the pores between the media particles and the microorganisms living there feed on the waste materials, removing them from the water. The size of the media particles greatly affects the system's ability to their function. With the small pores (30% bulk porosity) and high surface area of the porous media could help to filter small molecule of pollutants contained in the wastewater. Meephon [10] developed the high-efficiency porous media (made of 60% of laterite soils, 20% of charcoal, and 29% of bentonite powder) with high surface area for P and organic matters removal.

Due to its exceptionally high surface area (ranges from 500 to 1500 m^2/g), well-developed internal porosity, and wide spectrum of surface functional groups, activated carbon and biochar has been widely used in the CW and MSL and it has been proven to be an effective adsorbent for the removal of a wide variety of organic and inorganic pollutants from wastewater [11]. Activated char are made from the natural material such as nutshells, wood, coal and petroleum, and commonly available in largest size (8–30 mesh), medium size (12–40 mesh) and finest size (20–50 mesh). Wang et al. [12] reported that the biochar that was produced synthesized with $LaCl_3.6H_2O$ under the pyrolysis process could provide the best adsorption potential of NO_3-N. Zhou et al. [13] reported that the biochar-CWs could provide high treatment efficiencies for organic pollutants (85%), NH_4-N (39%), and TN (39%), which is about 10–20% higher than the CWs. Moreover, to enhance the interaction between media and microbe/plant, Gunarathne [14] reported that the physical microstructure of biochar has a great influence on the role of biochar in plant nutrient uptake to determine the accessibility of mineral constituents by soil solution and creating better conditions in the rhizosphere for microbes activities in CWs.

18.3 Natural Treatment Processes in Wetlands and Plant-Microbe Ecology

Organic materials contained in the wastewater (COD and BOD) are converted up to 50% carbon by microorganisms. The vast arrays of microorganisms are adapted for both aerobic and anaerobic conditions. The reduction of easily degradable organic compounds is the interactions with integrated chemical, physical and biological processes driven by microorganisms [15, 16]. In essence, oxygen production in the root zone and dissolved in the top layer of the MSL is used by aerobic microorganisms in organic matter decomposition (Respiration reaction, Eq. 18.1). Emergent plant oxygen transfer in CWs become important. Wu et al. [17] used hydroponic experiments to estimate 0.04 g O_2/m^2/day supplied by *Typha latifolia*, versus 0.60 g O_2/m^2/day provided by *Spartina pectinata*. Some plant species can rise transportation of oxygen by convective flow of gases [18]. Polprasert and Koottatep [19] found biofilm bacteria growing on surfaces of the media and root zones in the CW beds to be the major organisms responsible for BOD removal. Fermentation Eq. 18.2 and denitrification Eq. 18.3 reactions in the MSL also occurred in the middle and bottom of the system depending on the oxygen profile each CW layer.

Respiration (aerobic zone)

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \tag{18.1}$$

Fermentation (anoxic and anaerobic zone)

$$\begin{aligned} C_6H_{12}O_6 &\rightarrow 2CH_3CHOHCOOH \\ C_6H_{12}O_6 &\rightarrow 2CH_3CH_2OH + 2CO_2 \end{aligned} \tag{18.2}$$

Denitrification (anoxic and anaerobic zone)

$$C_6H_{12}O_6 + 4NO_3^- \rightarrow 6H_2O + 6CO_2 + 2N_2 + 4e^- \tag{18.3}$$

In addition to the N removal in ACW, zeolite has been utilized successfully as PL materials owing to its high cation exchange capacity (CEC) and adsorption capacity which could help to enhance Ammonia sorption reaction Eq. 18.4. Truu et al. [20] proposed in microbial ecology, broadened the knowledge about microbial communities in these systems and help to improve the design and performance of CWs. The dominant phylum of microorganisms to removal organic matters belonged to the Proteobacteria, Actinobacteria and Bacteroidetes. The phyla of Proteobacteria is the main metabolically diverse group equally diverse with the relationship to oxygen presence. With the produced endospores, Firmicutes are resistant to desiccation and can survive extreme conditions. The species of *Clostridia* (anaerobe), *Bacilli* (obligate or facultative aerobes) are normally found as the group of Firmicutes (endospore-forming bacteria) in the MSL and CW systems [21]. The main habitat of *Clostridia* are present in soil layer together with many anaerobic energy-yielding mechanisms [22].

Bacilli produces extracellular hydrolytic enzymes to break down complex polymers such as polysaccharides and lipids, etc. Being nutrients, N and P are uptaken by emergent plants for their growth and removed from the influent wastewater. The range of N and P removal by plants uptake were reported to be 10–50% [19]. Nitrification and denitrification can also be significant reactions responsible for N removal in MSL systems if suitable environmental conditions conductive to the growth of nitrifying bacteria (high DO) and denitrifying bacteria (low DO) are maintained Eqs. 18.5, 18.6 and 18.7.

Koottatep et al. [5] reported that there were more abundance of ammonia oxidizing archaea (AOA) and ammonia oxidizing bacteria (AOB) in the MSL beds than those in the CW bed which presumably oxidized NH_3-N to become NO_2-N and NO_3-N. These NO_3-N would have been further denitrified to become N_2 gas by the denitrifying bacteria, resulting in effective NH_3-N removal. The higher abundance of the AOA and AOB in the MSL units indicates the positive effects of the novel MSL media in supporting the microbial growth responsible for NH_4^+-N and also COD and BOD removal. Ammonia oxidation, the oxidation of ammonia to nitrate via nitrite, is the first step of nitrification carried out by ammonia-oxidizing archaea (AOA) and bacteria (AOB). Ammonia oxidation. Denitrification is the process in which nitrate is converted into N_2 via intermediates nitrite, nitric oxide and nitrous oxide under anoxic condition [23]. *Nitrososphaera* cluster, which has been classified into the family of *Thaumarchaeota*, was AOA presenting in MSL. Most of the AOB sequences belonged to the cluster of *Nitrosospira* and *Nitrosomonas*.

Ammonia Sorption

$$RH^{+} + NH_4^{+} + OH^{-} \leftrightarrow RNH_4^{+} + H_2O \tag{18.4}$$

Nitration (Nitrosomonas)

$$2NH_4^{+} + 3O_2 \rightarrow 2NO_2^{-} + 2H_2O + 4H^{+} \tag{18.5}$$

Nitrification (Nitrobacter)

$$2NO_2^{-} + 2O_2 \rightarrow 2NO_3^{-} \tag{18.6}$$

Denitrification

$$\begin{gathered} NO_3^{-} + 0.833CH_3OH \rightarrow 0.5N_2 + 0.833CO_2 + 1.167H_2O + OH^{-} \\ (\text{Base on Methanol;}CH_3OH) \\ NO_3^{-} + 0.208C_6H_{12}O_6 \rightarrow 0.5N_2 + 1.25CO_2 + 0.75H_2O + OH^{-} \\ (\text{Base on Glucose;}C_6H_{12}O_6) \\ 84.8NO_3^{-} + (_C(_N(H_3PO_4) \\ \rightarrow 42.4N_2 + 106CO_2 + 148.8H_2O + 16NH_3 + H_3PO_4 \\ (\text{With P consideration}) \end{gathered} \tag{18.7}$$

P removal in MSL systems is due mainly to adsorption on the medias and precipitation, and was found to be about 40–60%. P tends to accumulate in the MSL at a higher rate than N due to the processes of sorption, decomposition, plant uptake and long-term storage occurrences. The common chemicals responsible used for P precipitation include aluminum (Al^{3+}), ferric iron (Fe^{3+}), ferrous iron (Fe^{2+}), and calcium (Ca^{2+}). It should be noted that chemical P removal is accomplished with the sedimentation process.

Precipitation

$$\begin{aligned} &Al^{3+} + H_nPO_4^{3\ n} \rightleftharpoons AlPO_{4(s)} + nH^{+} \ (\text{by aluminum salt; pH} = 3.5-5) \\ &Fe^{3+} + HnPO_4^{3\ n} \rightleftharpoons FePO_{4(s)} + nH^{+} \ (\text{by iron salt; pH} = 6.0-6.3) \end{aligned} \tag{18.8}$$

The iron added in the soil layer and MB is transformed into ferrous iron (Fe^{2+}), which is subsequently translocated to the zeolite interlayer and is oxidized to ferric ion (Fe^{3+}), which aids in associating coprecipitation of PO_4^{3-}-P from the percolating wastewater. The N and P removal mechanisms are shown in Table 18.2.

Table 18.2 Removal mechanisms of N and P

Pollutant	Type	Removal mechanisms
N series	NH_4^+-N	Oxidation and adsorption process
	NH_3-N	Biological, ammonification and adsorption process
	NO_3^-N	Biological and plant uptake process
	NO_2^--N	Biological, denitrification and plant uptake process
P		Precipitation process and adsorption

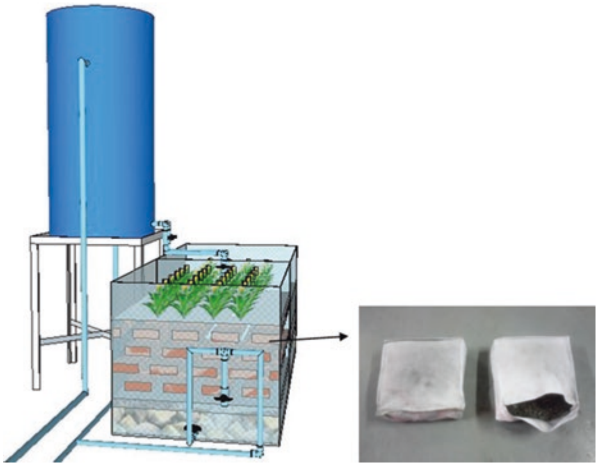


Fig. 18.3 MSL systems with larger MB surface area

Structures and configurations of the MSL systems have a strong influence on the treatment performance, especially the size of the MB layer. The MSL systems with larger MB surface area (about 40–60% of the total surface area) could enhance contact efficiency between wastewater and MB, resulting in higher removal rates of suspended solids, BOD, COD and nutrients. An increase in the horizon area of MB was found to increase the performance of MSL systems more than an increased vertical surface area of MB. Chen et al. [24] and Vymazal [25] reported that effective contact between the system and wastewater was are the main factor to achieve a high treatment for organic decomposition (Fig. 18.3).

With the low C/N ratio of the wastewater, the increasing PL proportion should be considered to removing of NH_3-N. The enhancement and maintenance of contact times between of the MB and wastewater are important at the HLR of 500–5000 L/m^2/day depending on the wastewater characteristics. For the design factor of the MSL structural and width ratio, increasing the number of MB could also provide a positive result for treatment performance and preventing clogging in the long term. To enhance the treatment capacities of the MSL, the number of vertical MB layers should be increased by reducing the spacing of each layer of the ACW. To control/

design with the proper permeability of MB by using highly permeable materials, the porosity of media should be measured by void volume measurement method (by filling the media into the volume container and then filled the water until the water level reached the top of the media) and calculated as

$$\text{Porosity} = V_{void} / V_{total} \quad (18.9)$$

where V_{void} = Pore space volume in the container and V_{total} = Total volume of the container. The porosity of each material was 0.4 for lateritic soil, 0.2 for sawdust, 0.1 for powdered charcoal, 0.4 for zeolite, 0.4 for fine gravel and 0.5 for coarse gravel.

18.4 Treatment Performance of ACWs: Organic Matters, Emerging Pollutants and Nutrients

The ACWs are found to have relatively high treatment efficiencies in removing organic matters, emerging pollutants, and nutrients (Table 18.3). Koottatep et al. [26] and Vo et al. [27] investigated the medias (such as Arlitra, gravel laterite soil, activated carbon, cement and crushed shellfish) suitable to enhance the treatment efficiencies of the emerging pollutants in the ACWs. The results found that there is a relative consequence between H_2O_2 concentration and Fe concentration in the medias in reduction of emerging pollutants in the wastewater. The aeration system was applied in several studies [28–30] by promoting the aerobic decomposition. However, excession aeration rate of the MSL system could result in decreasing denitrification rate, and the translocation of ferric hydroxide from the MB to PLs resulting in decreased N and P removal efficiencies [7].

The ACW are more efficient and robust in wastewater treatment than other soil-based systems such as CWs or compact filter systems. Typically, CWs have abilities for removal rates ranging from 60% to 95% of organic matter or many pollutants [31]. Sato et al. [32] reported that during 2 years of operation, the MSL system in Matsue city, Japan, showed much higher removal rates for BOD, P and N than the conventional CW system. The ACW system with an area of around 4.4 m^2, had the removal rates for BOD, N and P higher than 80–90%. The mechanism of P removal in the MSL system was due mainly to metal iron in soil mixture block oxidized to ferrous ion, which was then transferred to zeolite layer and oxidized further to ferric ion and deposited on zeolite particles as hydroxides which could fix phosphate ion as well as iron as a component of soil [7]. It was estimated that the long-term elimination rate of the P through plants is about 0.05 g/m^2/day in the CW system.

Masunaga et al. [30] found that the removal percentages of the MSL system tp range from 90% to 96% for SS, from 88% to 98% for BOD, from 83% to 94% for COD, from 44% to 57% for T-N, and from 63% to 89% for T-P at HLR of 500–2000 L/m^2.day. Moreover, MSL systems could receive a loading rate around 50 times that of CW. with a BOD amount more than 10 times higher than that flowed into CWs [33]. Similar to Unno et al. [34] implemented the MSL for the treatment of Kumazoi river water in Kyushu, Japan, for about one-year operation.

Table 18.3 Performance of ACWs in removing pollutants

Plant	Media	Type of wetland	Study	Mechanism	Study area[a]	References
Scirpus validus	Laterite soil, activated carbon, cement and crushed shellfish	VSF	Removal of acetaminophen by modified soil compositions	Chemical $Fe_2^+ + H_2O_2 \rightarrow Fe_3^+ + HO^- + OH$ $Fe_3^+ + H_2O_2 \rightarrow Fe_2^+ + HO^2 + H^+$	Thailand	[26]
Scirpus validus	Sand, pea gravel and gravel	VSF	Removal and monitoring acetaminophen-contaminated hospital wastewater	Peroxidase enzymes to alleviate pollutants' stress Peroxidase + $H_2O_2 \rightarrow$ Peroxidase1 + H_2O	Thailand	[27]
Unplanted	MSL (zeolite, zeolitized perlite, perlite, gravel, and charcoal) and sandy clay soil, kenaf + corncob, and iron scraps at a ratio of6: 1: 1 by weight)	VSF+ Aeration	Treating normal pollution (COD, TS, N, P, etc.)	Adsorption, filtration and precipitation process	Thailand	[28]
Unplanted	MSL (Soil, charcoal, sawdust, and iron), gravel, pumice. Perlite or zeolite	VSF+ Aeration	Low cost sustainable technologies for decentralized wastewater treatment, treating normal pollution (COD, TS, N, P, etc.)	Adsorption, filtration and precipitation process	Morocco	[29]
Unplanted	MSL (volcanic ash soil, sawdust and granular metal iron), charcoal, and zeolite	VSF+ Aeration	CO_2, CH_4 and N_2O emissions from MSL system	—	Japan	[39]

[a]The average ambient temperature ranges in each of the study areas (referred to the average annual temperature of each country): Thailand (28–33 °C), Morocco (12–29 °C), Japan (5–26 °C)

Table 18.4 First-order of coefficients treatment parameters of ACW units

	First-order coefficients and plug flow model			First-order coefficients and complete-mixed model		
Parameters	k_{30} (d^{-1})	R^2	k_{20} (d^{-1})	k_{30} (d^{-1})	R^2	k_{20} (d^{-1})
COD	0.327	0.94	0.2682	1.734	0.965	1.4224
BOD	0.318	0.95	0.2615	1.876	0.970	1.5392
NH_3-N	0.528	0.95	0.4337	12.59	0.980	10.328

The amount of BOD discharged into MSL systems was 64 g/m^2/day 6–12 times had higher treatment capacity than that of the conventional soil trench systems. Kadam et al. [35] reported the performance of municipal wastewater treatment plant located at Mumbai, India, using laterite soil-based CW system with the low HRT and high HLR. The results showed the trend of DO to increase, and the effluent concentrions of COD and BOD decreased from 135 to 28.8 mg/L and 92 to less than 10 mg/L, respectively. In the case of biochar application in the CWs, Zhou et al. [13] reported that t combining VFCWs and biochar addition could be an appropriate strategy as compared to conventional VFCWs with an average removal of organic pollutants (85%), NH_4^+-N (39%), and total nitrogen (39%), especially at high influent strengths. Meanwhile, N_2O emissions were about 138–1008 μg/m^2/h in biochar-added VFCWs lower than that in non-biochar-added VFCWs which were about 164–1304 μg/m^2/h.

Koottatep et al. [5] developed the first-order of coefficients of ACW in both the completely-mixed flow and plug-flow models by using data of the COD, BOD and NH_3-N removal efficiencies and calculated the correlation coefficient (R^2) values to determine the best fit model. Due to the structure of the MSL, the first-order completely- mixed model had slightly higher R^2 values, suggesting it to be the best-fit model for the ACW units. A previous study, Reddy and Debusk [36] reported that the kinetic coefficient of BOD removal in aquatic pond to be about 1.104 d^{-1}, less than the value of 1.539 d^{-1} of the ACW (Table 18.4). Reed et al. [37] reported that the kinetic coefficient of NH_3-N removal of ecological treatment system was found to be 0.129 d^{-1} lower than the kinetic coefficient of NH_3-N removal from this study, which was about 10.382 d^{-1}.

18.5 Application of Advanced Constructed Wetlands for Pollution Mitigation: Case Studies in Hot Climate Countries

18.5.1 Performance of Novel Constructed Wetlands for Treating Solar Septic Tank Effluent [38]

The pilot-scale ACW and modified constructed wetland (mCW) units were operated in parallel during the period of 2016–2019 under the same conditions (unit configurations, plant species and operational parameters). This study aimed to investigate

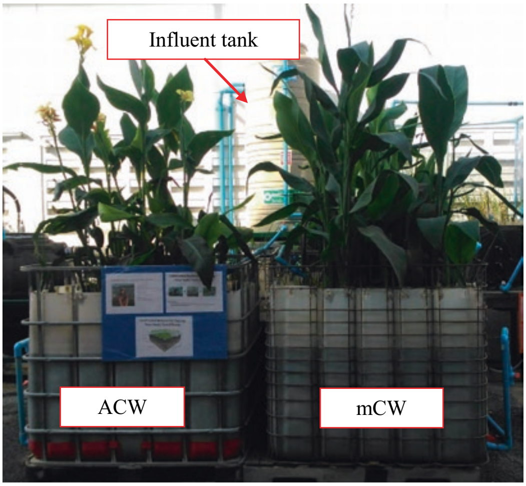


Fig. 18.4 ACW vs mCW

the treatment performance of the ACW and comparing with the modified constructed wetland (mCW) in treating solar septic tank effluent in long-term operation. The pilot-scale ACW and mCW units (Fig. 18.4), made of rectangular plastic tanks, were installed and operated in parallel at the Asian Institute of Technology campus, Pathumthani, central Thailand, in 2016 with the range of temperature of 28–33 °C. Dimensions of each experimental unit were 94 cm (width) × 115 cm (length) × 87 cm (height), with a surface area of 1.08 m^2. Canna sp. was planted on the zeolite of the ACW unit and on the clay loam layer of the mCW unit, and the space between each plant was about 15 cm.

The ACW unit consisted of soil mixture block (SMBs), permeable layer (PLs) and underdrain layers. The SMBs was the mixed composition on dry weight basis of lateritic (or iron-rich) soil (80%), sawdust (10%) and charcoal (10%). Powdered charcoal with sizing smaller than 0.1 mm was the porous material. The mixtures of SMBs were packed into fiber bags, each with a size of 15 cm (width), 5 cm (height) and 15 cm (length). The PLs comprised of zeolite (a clinoptilolite type) approximately 3–5 mm in diameter. The underdrain layers consisted of 15 cm of coarse gravel (3–5 cm in diameter) at the bottom, 5 cm of fine gravel (2–3 cm in diameter) in the middle. The mCW unit consisted of four layers of 20 cm of clay loam (size smaller than 3 cm) at the top, 10 cm of lateritic soil (size smaller than 3 cm and Fe content of 20 g/kg) at the second layer, 5 cm of fine gravel at the third layer, and 20 cm of coarse gravel at the bottom.

The removal efficiencies of SCOD and TBOD in the ACW were not significantly different ($p < 0.05$) when compared with the mCW unit, which were 63–68% and 78–82%, respectively. During the 4-year operation, there was not much variation in the effluent concentrations of organic matters of the ACW and mCW, with the average TCOD concentrations of 35 ± 18 and 34 ± 15 mg/L, respectively, followed by SCOD (24 ± 14 and 26 ± 12 mg/L, respectively) and TBOD (5 ± 3 and 6 ± 4 mg/L, respectively). The concentrations of TCOD in the effluent of the ACW and mCW units over the 4-year operation were lower than the global standard (ISO30500, Catagory A and B) of ≤50 mg/L. The decreasing trend of the TKN and NH_4-N concentrations in the ACW was probably due to the simultaneous existence of nitrification-denitrifications reactions with various microbial abundances inside the SMB and PL, which facilitated the conversion of TKN and NH_4-N to N_2 (Fig. 18.5).

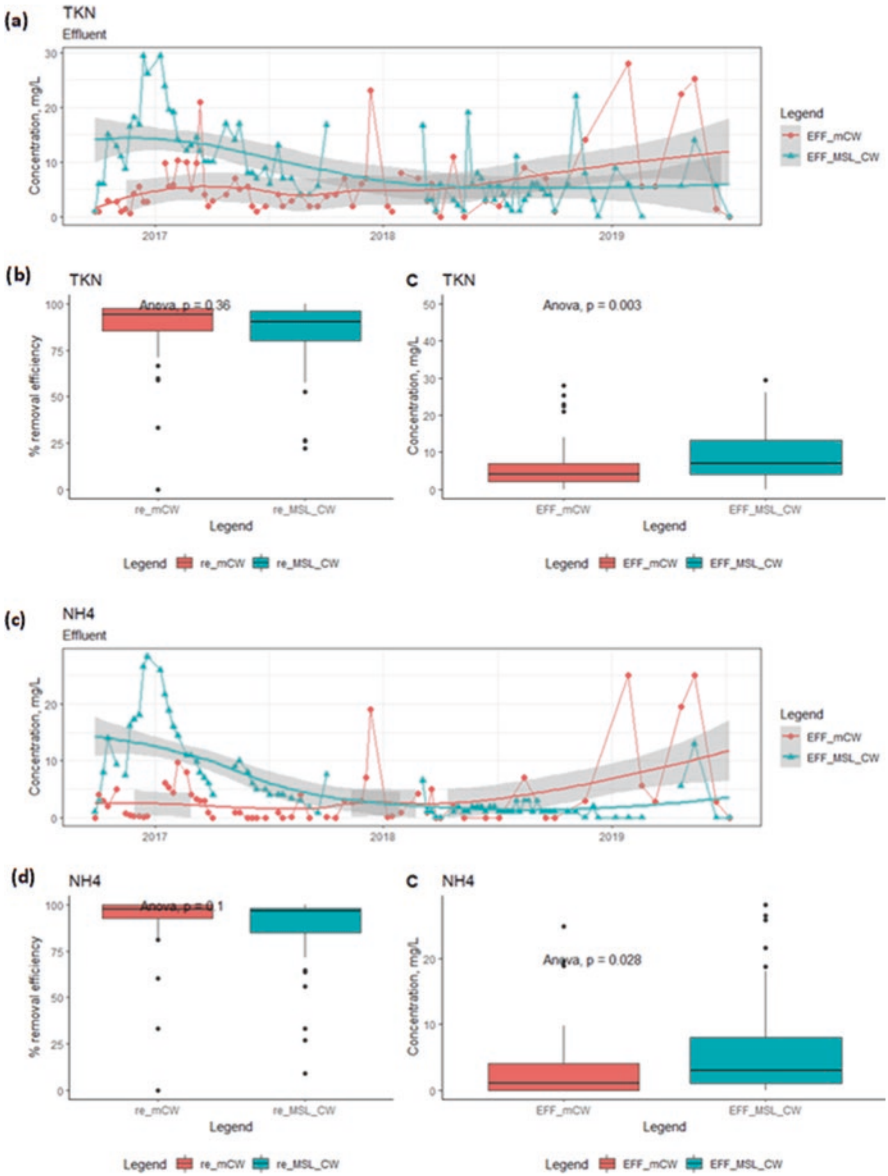


Fig. 18.5 (**a**, **b**) TKN and (**c**, **d**) NH_4-N concentrations in the ACW and mCW (removal efficiency (re) and concentration (EFF))

This suggests that the ACW could achieve better TKN and NH_4-N removal efficiencies in the long run. The zeolite material in the ACW system adsorbs the NH_4^+-N ions in the wastewater through ion exchange mechanism and serves as carrier for nitrifying bacteria to convert the intermediate nitrogen (Nitrate nitrogen, NO_3-N), which can translocate to the SMB, and promote the denitrification under anaerobic conditions [33]. The effluent concentrations of TP were found in the same magnitude for both units, being about 1 ± 2 mg/L. Total coliform and E. coli counts in the effluent of both ACW and mCW units were apparently reduced to the concentrations lower than 10^2 MPN/100 mL without disinfection unit. Over the long-term operation, the designed MSL system could likely provide stability to the base media in subsurface infrastructure and minimize the decrease in their drainage capacity.

18.5.2 Integration of the Innovative On-site Wastewater Treatment and ACW System Without Plants for Treating Black Water [39]

The integrated up-flow solar septic tank (UTST) and ACW system without plants has been developed under actual conditions of fluctuating flow rates, ambient temperatures and black water characteristics at communal toilets located at the Asian Institute of Technology campus, Pathumthani province, central Thailand (Fig. 18.6). The UTST effluent was discharged by gravity without any energy input to the ACW unit designed as a specialized multi-cell subsurface vertical flow which had a dimension of 87 × 94 × 115 cm (working high × width × length), and the designed hydraulic retention time of 24 hours and organic loading rate of 4 g/L.d. The MSL of ACW unit was composed of soil mixture boxes (with a ratio of laterite soil mixed with sawdust and powdered charcoal at 80, 10 and 10%, respectively, on dry weight basis), and the permeable layers were composed of zeolite (clinoptilolite type).

The treatment performance of the integrated UTST and MSL unit during the 1 year operation period showed the average treatment efficiencies of 92 ± 10% for TCOD, 79 ± 10% for SCOD, 93 ± 9% for TBOD and 90 ± 12% for SBOD. The superior performance of the ACW unit in removing NH_3 of 98 ± 2% was higher than

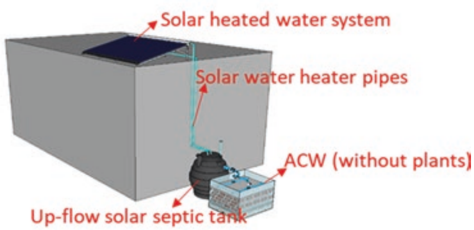


Fig. 18.6 A field testing of the integrated UTST and ACW system

the UTST unit (39 ± 16%). The average removal efficiencies of TCOD, SCOD, TBOD and SCOD of the integrated UTST and ACW units during the operation period were found in the range of 90–99%. An increase in removal rates by ACW unit could produce the treated effluent in compliance with the ISO requirements. The effluent TCOD, TBOD, TKN, NO_2-N, NO_3, NH_3 and TP concentrations of the ACW were 39 ± 27, 8 ± 27, 5 ± 5 mg/L, 2 ± 2, 39 ± 24, 8 ± 9, 2 ± 5 and 1 ± 1 mg/L, respectively. These results indicated that the nouveau design solar septic tank could effectively promote the biodegradation of the organic matters, and convert those nutrients into final products (N_2), resulting in high treatment performance.

During the 1-year operation period, the average effluent TCOD concentration was lower than 50 mg/L meeting the ISO30500 Category A standard. Compared to TN and TP requirements by the ISO30500 Category A, i.e., 70% and 80% removal efficiencies of TN and TP, respectively, the nouveau design solar septic tank could satisfactorily achieve an overall TN (the sum of TKN, NO_2-N and NO_3-N) and TP removal efficiencies of 95% and 98%, respectively. During the operation period, the main reasons for the low TKN and NH_3 removal in these UTST and ACW units could be the low TBOD/TKN ratios of the influent black water. Increasing the TBOD/TKN ratios of the influent feed could be achieved through installing urine-diversion toilets to separate the urine (containing high NH_3-N) from the influent black water.

18.6 Conclusion

The conceptual design of ACW with the newly-modified media and unit configuration (media arrangement) is considered novel CW for efficiently treating wastewater in hot climate regions. The novel media concept for ACW is arranged in a brick-like pattern and combined with soil, sawdust, zeolite and biochar in a suitable ratio depending on the wastewater type and characteristics. Unit configuration inside ACW should be arranged by laying a series of mixed-media block (MB) layer with permeable layer (PL) and place the underdrain layer (UL at the bottom). The newly-developed media and its rearrangement in the ACW unit could achieve the desired treatment levels at the relatively small footprint (reducing surface area requirement of about 10–20%). In addition, the system has been found to be more efficient in treating organic matters and nutrients than other soil-based systems such as conventional CW or compact filter systems. The ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) were found to be present in the layers of MSL which played a major role inconverting ammonia to nitrogen gas. The advanced constructed wetlands with tropical plant species possess the ability to break down some pharmaceutical and personal cares products (PPCPs). With high treatment efficiencies and effluent quality, the ACW units could demonstrate their innovations which should be considered as a promising wastewater treatment technology. The concept design could offer enormous opportunities for achieving degradations of contaminants present in domestic wastewater or septic tank effluent by exploiting the cooperative and mutualistic metabolisms between plants and microbial communities in both plant rhizosphere and novel media layers. The monitoring results obtained from more than 2 years of operation indicated that ACW units are very effective in removing organic matters and nutrients in the wastewater and able to comply with the global discharge standard requirements such as ISO30500 and WHO guidelines for wastewater reuse.

References

1. Henze M, Ledin A (2001) Types, characteristics and quantities of classic, combined domestic of classic, combined domestic. In: Len P, Zeeman G, Lettinga G (eds) Decentralised sanitation and reuse, concepts, systems and implementation. IWA Publishing, London, UK
2. Polprasert C, Rajput VS (1982) Septic tank and septic systems: environmental sanitation reviews. Environmental Sanitation Information Center. Asian Institute of Technology, Thailand
3. Sharma MK, Kazmi AA (2015) Anaerobic onsite treatment of black water using filter-based packaged system as an alternative of conventional septic tank. Ecol Eng 75:457–461
4. U.S. EPA (2002) Onsite wastewater treatment system manual. United States of America: Environmental Protection Agency, Washington D.C.
5. Koottatep T, Suksiri P, Pussayanavin T, Polprasert C (2018) Development of a novel multi-soil layer based constructed wetland treating septic tank effluent with emphasis on organic and ammonia removal. J Water Air Soil Pollut 229(8):1–10
6. Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'neill B, Neves EG et al (2006) Black carbon increases cation exchange capacity in soils. Soil Sci Soc Am J 70(5):1719–1730
7. Wakatsuki T, Esumi H, Omura S (1993) High performance and N&P removal on-site municipal wastewater treatment system by multi-soil-layering method. Water Sci Technol 27(1):31–40
8. Luanmanee S, Boonsllk P, Attanandana T, Saitthiti B, Panichajakul C, Wakatsuki T (2002) Effect of intermittent aeration regulation of a multi-soil-layering system on municipal wastewater treatment in Thailand. Ecol Eng 18:415–428
9. Attanandana T, Saithiti B, Thongpae S, Kritapirom S, Wakatsuki T (1997) Wastewater treatment study, using the multi-soil-layering system. In: Soil quality management and agro-ecosystem health, Proceedings of the Fourth international conference on soil quality management and agro-ecosystem health. Cheju (Korea), pp 417–426. https://kukr.lib.ku.ac.th/kukr_es/BKN_AGRI/search_detail/result/25516
10. Meephon S (2017) Hybrid constructed wetlands for phosphorus removal and purifications of eutrophic pond water. Master Thesis No. EV-17-19, Asian Institute of Technology. Asian Institute of Technology, Bangkok
11. Bansal RC, Goyal M (2005) Activated carbon adsorption. CRC Press
12. Wang Z, Guo H, Shen F, Yang G, Zhang Y, Zeng Y, Deng S et al (2015) Biochar produced from oak sawdust by Lanthanum (La)-involved pyrolysis for adsorption of ammonium (NH4+), nitrate (NO3−), and phosphate (PO43−). Chemosphere 119:646–653
13. Zhou X, Wang X, Zhang H, Wu H (2017) Enhanced nitrogen removal of low C/N domestic wastewater using a biochar-amended aerated vertical flow constructed wetland. Bioresour Technol 241:269–275
14. Gunarathne V, Mayakaduwa S, Vithanage M (2017) Biochar's influence as a soil amendment for essential plant nutrient uptake. In: Essential plant nutrients. Springer, Cham, pp 47–67
15. Nicomrat D, Dick WA, Tuovinen OH (2006) Assessment of the microbial community in a constructed wetland that receives acid coal mine drainage. Microb Ecol 51(1):83–89
16. Tietz A, Kirschner A, Langergraber G, Sleytr K, Haberl R (2007) Characterisation of microbial biocoenosis in vertical subsurface flow constructed wetlands. Sci Total Environ 380(1):163–172

17. Wu CH, Chang HS, Kao TC et al (2001) Environment-controlled hydroponics inside subtropical air-inflated greenhouses. In: ISHS Acta Horticulturae 578, International Symposium on Design and Environmental Control of Tropical and Subtropical Greenhouses. https://doi.org/10.17660/ActaHortic.2002.578.28
18. Armstrong W, Cousins D, Armstrong J, Turner DW, Beckett PM (2000) Oxygen distribution in wetland plant roots and permeability barriers to gas-exchange with the rhizosphere: a microelectrode and modelling study with Phragmites australis. Ann Bot 86(3):687–703
19. Polprasert C, Koottatep T (2017) Organic waste recycling: technology, management and sustainability. IWA Publishing, Amsterdam
20. Truu M, Juhanson J, Truu J (2009) Microbial biomass, activity and community composition in constructed wetlands. Sci Total Environ 407(13):3958–3971
21. Desta AF, Assefa F, Leta S, Stomeo F, Wamalwa M, Njahira M, Appolinaire D (2014) Microbial community structure and diversity in an integrated system of anaerobic-aerobic reactors and a constructed wetland for the treatment of tannery wastewater in Modjo, Ethiopia. PLoS One 9(12):e115576
22. Madigan M, Martinko J (2012) Brock biology of microorganisms, 13th edn. Benjamin Cummings, San Francisco, USA
23. Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380(1):48–65
24. Chen X, Sato K, Wakatsuki T, Masunaga T (2007) Effect of aeration and material composition in soil mixture block on the removal of colored substances and chemical oxygen demand in livestock wastewater using multi-soil-layering systems. Soil Sci Plant Nutr 53(4):509–516
25. Vymazal J (2010) Constructed wetlands for wastewater treatment. Water 2(3):530–549
26. Koottatep T, Chapagain SK, Vo NP, Hoang V, Panuvatvanich A, Polprasert C, Iamchaturapatr J (2017) Modified soil compositions for removal of acetaminophen from wastewater. In: Key engineering materials, vol 751. Trans Tech Publications Ltd, Zurich, pp 677–682
27. Vo HNP, Koottatep T, Chapagain SK, Panuvatvanich A, Polprasert C, Nguyen TMH et al (2019) Removal and monitoring acetaminophen-contaminated hospital wastewater by vertical flow constructed wetland and peroxidase enzymes. J Environ Manag 250:109526
28. Boonsook P, Luanmanee S, Attanandana T, Kamidouzono A, Masunaga T, Wakatsuki T (2003) A comparative study of permeable layer materials and aeration regime on efficiency of multi-soil-layering system for domestic wastewater treatment in Thailand. Soil Sci Plant Nutr 49(6):873–882
29. Lamzouri K, Mahi M, Ouatar S, Bartali E, Masunaga T, Latrach L, Mandi L (2016) Application of multi-soil-layering technique for wastewater treatment in Moroccan rural areas: study of the operation process for an engineering design. J Mater Environ Sci 7(2):579–585
30. Masunaga T, Sato K, Senga Y, Seike Y, Inaishi T, Kudo H, Wakatsuki T (2007) Characteristics of CO2, CH4 and N2O emissions from a multi-soil-layering system during wastewater treatment. Soil Sci Plant Nutr 53(2):173–180
31. Tousignant E, Eng P, Fankhauser O et al (1999) Guidance manual for the design, construction and operations of constructed wetlands for rural applications in Ontario, Stantec Consulting Ltd. http://agrienvarchive.ca/bioenergy/download/wetlands_manual.pdf. Accessed 11 Nov 2016
32. Sato K, Iha Y, Luanmanee S et al (2002) Long term on-site experiments and mass balances in wastewater treatment by multi-soil-layering system. In: Proceedings of the 17th world congress of soil science, Bangkok, Thailand, 14–21 Aug 2002
33. Chen X, Luo AC, Sato K, Wakatsuki T, Masunaga T (2009) An introduction of a multi-soil-layering system: a novel green technology for wastewater treatment in rural areas. Water Environ J 23(4):255–262
34. Unno S, Wakatsuki T, Masunaga T, Iyota K (2003) Study on direct treatment of river by multi-soil-layering method and its characteristics of water purification. Jpn Soc Civ Eng 726:121–129
35. Kadam AM, Nemade PD, Oza GH, Shankar HS (2009) Treatment of municipal wastewater using laterite-based constructed soil filter. Ecol Eng 35(7):1051–1061

36. Reddy KR, Debusk TA (1987) Utilization of aquatic plants in water pollution control. Water Sci Tech 19(10):61–79
37. Reed SC, Crites RW, Middlebrooks EJ (1995) Natural systems for waste management and treatment, 2nd edn. McGraw-Hill, New York
38. Koottatep T, Pussayanavin T, Kamyai S, Polprasert C (2020) Performance of novel constructed wetlands for treating solar septic tank effluent. Sci Total Environ
39. Koottatep T, Pussayanavin T, Polprasert C (2020) Nouveau design solar septic tank: reinvented toilet technology for sanitation 4.0. Environ Technol Innov 19:100933

Chapter 19
Treatment Wetlands in Atacama Desert, Chile: Experiences and Lesson Learnt from Wastewater Treatment and Reuse

Ismael Vera-Puerto, Marcos Bueno, Jorge Olave, Rocío Tíjaro-Rojas, Binita Gandhi, and Carlos A. Arias

Abstract The Atacama Desert situated along the northern Chile is known as the driest desert in the world. For several years, the Research and Development Center in Water Resources (CIDERH), Arturo Prat University has been promoting applied research to encourage the use of wetlands for treating polluted waters in this unique environment and its communities. Focused on gathering information using mesocosms set-ups and designing prototypes, CIDERH installed two experimental units on the coastal area at 37 m.a.s.l. (Iquique)., and another experimental unit placed on the mountains area about 1000 m.a.s.l. (Pampa del Tamarugal) for gathering information on reuse. The purpose was to evaluate the constructed wetlands as an alternative for wastewater treatment and reuse in small towns geographically distanced in the desert. Taking this experience into account, this chapter includes an introduction describing the geographical distribution, demographics, climatology, and water

I. Vera-Puerto (✉) · M. Bueno
Centro de Innovación en Ingeniería Aplicada (CIIA), Departamento de Obras Civiles, Facultad de Ciencias de la Ingeniería, Universidad Católica del Maule, Talca, Chile
e-mail: ivera@ucm.cl; bmarcos@ucm.cl

J. Olave
Centro de Investigación y Desarrollo en Recursos Hídricos (CIDERH), Universidad Arturo Prat, Iquique, Chile
e-mail: jorge.olave@ciderh.cl

R. Tíjaro-Rojas
Carrera de Ingeniería Civil Ambiental, Facultad de Ingeniería y Arquitectura, Universidad Arturo Prat, Iquique, Chile
e-mail: rtijaro@unap.cl

B. Gandhi
Department of Civil Engineering, University of Victoria, Victoria, BC, Canada

C. A. Arias
Department of Biology – Aquatic Biology, Aarhus University, Aarhus C, Denmark

WATEC Aarhus University Centre for Water Technology, Aarhus C, Denmark
e-mail: carlos.arias@bios.au.dk

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_19

resources for the Atacama Desert, and further discusses wastewater topics. This encompasses characteristics, regulations (i.e. management, discharge, and reuse), and both large scale (urban) and small scale (rural) treatment technologies. Beyond this assessment, a description of the performance of various experiments based on subsurface flow wetlands to treat municipal wastewater is presented. The efficiency of wetlands that contain various types of plants filled with reactive substrate is tested. Finally, the reclamation of treated effluent as irrigation water is discussed whilst considering the need for sustainable water management in arid areas to comply with the UN Sustainable Development Goals. The test of ornamental flowers growing in aeroponic systems irrigated with effluents treated with different wastewater treatment technologies (including treatment wetlands) provides an interesting result for this chapter. The large-scale application of these technologies constitutes an opportunity for the sustainability of water resources and improvements in the quality of life. This will benefit inhabitants of the multiple sparsely populated and remote communities of the vast territory that constitutes the Atacama Desert.

Keywords Atacama Desert · Chile · Lily flower · Reuse · *Schoenoplectus* spp. · Treatment wetlands · Constructed wetlands · Wastewater

19.1 The Atacama Desert

Located in the northern region of Chile, the Atacama Desert spans approximately 1000 km and is considered one of the most arid deserts in the world. Its area covers the regions of *Coquimbo*, *Atacama*, *Antofagasta*, *Tarapacá,* and *Arica y Parinacota*, approximately totaling 300,904 km^2. The population of the Atacama Desert is concentrated within urban areas (89%, approximately 2 million inhabitants), living in cities such as Arica, Iquique, Antofagasta, Calama, Copiapo, Chañaral, La Serena. These are mostly located on the shores of the Pacific Ocean. On the other hand, approximately 250,000 inhabitants (11%) live in rural areas, mainly in the region of Coquimbo (approximately 60%) [1].

According to the Köppen climatic classification [2, 3], the *BW* desert classification dominates: 66% of its surface (Fig. 19.1) is influenced by the presence of abundant cloudiness (index *n*) near coastal areas, while the cold area is transitioning (with annual average temperature under 18 °C; index *k*) to tropical conditions (index *i*) into the desert area [4]. The other regions are divided between the typology of Tundra (*ET*) and semiarid (*BS*), at approximately 25% and 8%, respectively. The rest of the region is composed of cold (*Csc*) and hot (*Csb*) Mediterranean climates, located in the southwest portion of the Coquimbo region.

In the desert, streams are characterized by perennial flow and support dense in-stream wetlands [5]. The extreme aridity of the Atacama Desert is largely due to the presence of the Southeast Pacific Subtropical Anticyclone (SPSA). The considerable subsidence of air produced by the anticyclonic circulation creates a stable layer

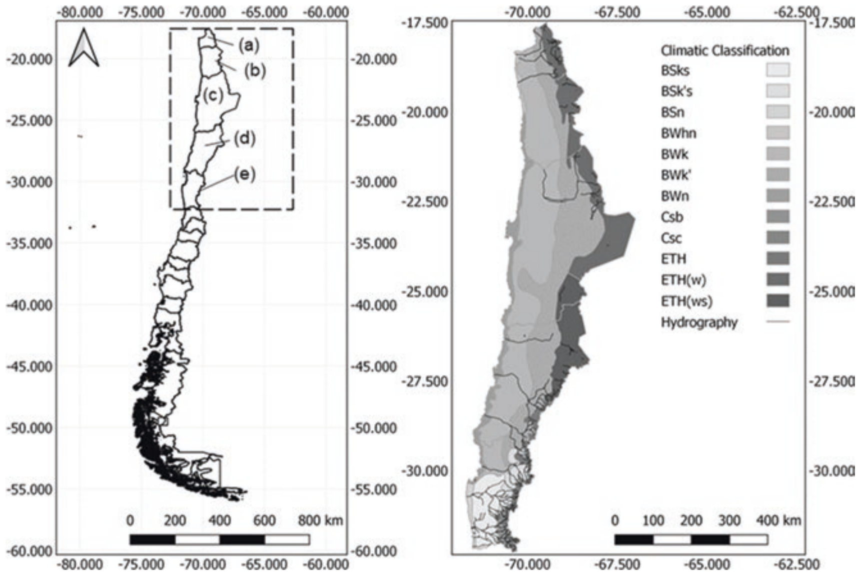


Fig. 19.1 Location of the Atacama Desert (left side), and Köppen climatic classification (right side). The letters on the upper right side of the map to the left refers to Chilean regions, where (**a**) is Arica and Parinacota, (**b**) Tarapacá, (**c**) Antofagasta, (**d**) Atacama, and (**e**) is Coquimbo. (Data Source: UFRO [8])

with very low moisture content, inhibiting the development of cloudiness and precipitation between the western part of the Andes [6]. The hyperaridity of the Atacama Desert is determined by two factors: the cold waters of the Humboldt current that reduce the evaporation capacity of waters from the Pacific Ocean to the atmosphere, and the topographic effects of the Costa Mountain Range, coastal *Farellón,* and its height, which block oceanic influences from to passing inland [7].

The summer precipitation regime in the northernmost part of the Atacama Desert is associated with the Alta de Bolivia regime, contributing to convection in the region. The transport of humidity at low levels is the result of the South American monsoon, which favors the formation of storms that generate rainfall during the summer. This results in an abrupt increase of streamflow's in the area, which is intensified by the topographical variances. Convective summer precipitation can reach the regions of Antofagasta and the northern part of Atacama, whereas cold fronts can bring rainfall to the middle and southern reaches of the Atacama Desert during winter. While the amount of precipitation during summer is much more significant than in winter, the intensity decreases as it enters the continent because of the Andes effect [9]. The central desert region has an estimated precipitation of 2 mm/year [10].

Due to scarcity of precipitations occurring mainly between January to April (austral summer) and a high evapotranspiration rates, water resources are scarce in Atacama Desert. Table 19.1 shows the availability and usage of water resources in

Table 19.1 Water resources and their use in Atacama Desert [11, 12]

Region	Runoff per capita (m^3/pe[a]/year)	Consumption by economic activity (m^3/s)			
		Agricultural	Drinking water	Industry	Mining
Arica and Parinacota	725	3.71	0.96	0.25	0.00
Tarapacá	599	5.21	0.69	1.43	1.54
Antofagasta	47	3.31	1.68	1.29	6.26
Atacama	190	12.03	0.87	0.52	1.90
Coquimbo	908	27.19	1.89	0.25	0.71
Average	493.8	10.29	1.22	0.75	2.08

[a]*pe* Person equivalent

the Chilean regions located in the Atacama Desert. According to Table 19.1, the two most important economic activities (in terms of water demand) in the Atacama Desert are agriculture and mining. In the case of mining, 78% of the companies in Chile are dedicated to the extraction of different minerals are located in the northern of the country [11].

19.2 Wastewater into Atacama Desert: Characteristics and Management

Table 19.1 indicates that drinking water represents an important part of water consumption in the Atacama Desert. After the use of drinking water, wastewater is generated; therefore, knowing its characteristics in terms of pollutants content, flows rates, and regulations, are important parameters to be linked with the selection, design and performance improvement of wastewater technologies, such as treatment wetlands (TWs) or else known as constructed wetlands. Efficiency of reuse and improving the quality of discharges are clue topics on arid environments. In this sense, Table 19.2 shows the quality parameters of raw wastewater in the Atacama Desert. According to Henze et al. [13], this wastewater can be considered "moderate" to "concentrated". In addition, is important to note that these values are similar to other raw wastewaters in various arid areas worldwide and in other Chilean regions [14, 15].

In terms of quantity, and considering an urban population with an average consumption of drinking water of 172.8 L/pe/day [16] and a coefficient of return of 0.8, the potential produced flow of wastewater is between 3 and 4 m^3/s. For the rural population, considering the average consumption of 60 L/pe/day [17] and with the same coefficient of return of 0.8, the raw wastewater produced would be between 0.1 and 0.15 m^3/s. On the other hand, Fig. 19.2 shows the treatment technologies used in the region. The treatment coverage is nearly 100% in urban areas [16], whereas sewerage coverage is less than 25% in rural areas [18]; hence, the

Table 19.2 Raw municipal wastewater characteristics in Atacama Desert

Water quality parameter	Units	n	Average ± Standard deviation	Minimum	Maximum
T	°C	82	24.31 ± 2.32	16.50	28.50
pH	Units	82	7.66 ± 0.49	6.59	9.27
EC	dS/m	15	2.4 + 0.2	2.1	2.8
ORP	mV	15	−250.2 + 70.8	−327.1	−141
BOD_5	mg/L	50	262 ± 68	87	489
COD	mg/L	50	662 ± 217	412	1780
TSS	mg/L	50	241 ± 104	53	610
TKN	mg/L	38	54.87 ± 31.97	0.9	119
TN	mg/L	15	67.5 + 18.3	35.5	96.6
TP	mg/L	38	3.18 ± 4.21	0.2	24
FC	Log_{10} MPN/100 ml	52	7.5 ± 0.7	3.34	8.20

Data from Vera-Puerto et al. [11], Vera et al. [19]
T Temperature, *EC* Electrical Conductivity, *ORP* Oxidation Reduction Potential, BOD_5 5-day biological oxygen demand, *COD* chemical oxygen demand, *TSS* total suspended solids, *TKN* total Kjeldahl nitrogen, *TN* Total Nitrogen, *TP* total phosphorus, *FC* fecal coliforms, *MPN* most probable number

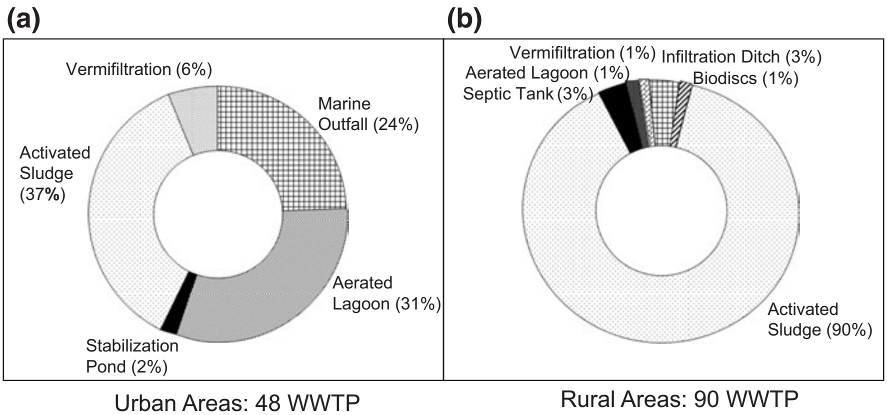


Fig. 19.2 Treatment technologies employed in Atacama Desert. (**a**) Centralized (urban); (**b**) Decentralized (including rural). *WWTP* wastewater treatment plant. (Data from: Vera-Puerto et al. [11] and SISS [20])

wastewater treatment coverage is even lower. This low coverage in rural areas shows the need of implementing technology according to the specific features of each territory. TWs can help to improve the coverage, since currently, as can be seen in Fig. 19.2, TWs are not employed at all in Atacama Desert. However, in order to this technology being implemented in this geographic area, previous steps as prototypes must be developed to evaluate different aspects such as effluents water quality, plants adaptations and developments, reuse opportunities, and other resources recovery.

The different wastewater treatment plants installed in this region are based on multiple technologies, which are shown in Fig. 19.2, and must comply with the Chilean discharge limits presented in Table 19.3. The most important regulatory document is the Supreme Decree 90 [21], which includes a comprehensive list of over 30 water quality parameters. It is important to note that Chile does not have specific regulations for wastewater reclamation and reuse [22]. The NCh 1333/Of. 87 [23] provides guidelines for the use of water in different activities (including water for irrigation). However, it does not consider the source of water (such as effluents from Wastewater Treatment Plant (WWTP)), where parameters of organic matter and solids are important to control in water quality for reuse in irrigation. These parameters are unfortunately not included in this regulation. Currently, new guidelines focused on wastewater reuse are being working on the country. This lack of reuse regulations could be an explanation for the lower reuse percentage, below 10% in terms of flow, in the Atacama Desert, as can be seen in Fig. 19.3. In addition, the Fig. 19.3 shows the final discharge or reuse of the effluents for centralized WWTPs (urban areas), where 64% of the treated wastewater, in terms of flow, are discharged into the sea. For decentralized WWTPs, no governmental or scientific published information is available yet. In this way, it is clear that alternatives of reusing effluents coming from wastewater treatment systems has to be studied to provide a better management of water resources for rural areas in this arid environment.

Table 19.3 Discharges limits for some selected water quality parameters in Chilean Regulations for continental and maritime territories [21, 24]

Water quality parameter	Units	Discharging place					
		Streams-1	Streams-2	Lakes	Sea-1	Sea-2	Aquifer
pH	Un.	6,0–8,5	6,0–8,5	6,0–8,5	6,0–9,0	5,5–9,0	6,0–8,5
BOD_5	mg/L	300	35	35	60	–	–
TSS	mg/L	300	80	80	100	300	–
TN[a]	mg/L	75	50	10[b]	50	–	10[d]–15[e]
TP	mg/L	15	10	2	5	–	–
FC	NMP/100 ml	1000	1000	1000–70[c]	1000–70[c]	–	–

Streams 1: streams with dilution capacity; Streams 2: streams without dilution capacity. Sea 1: within the coastal protection area; Sea 2: outside the coastal protection area

[a]In the regulation, TN is TKN

[b]The value in Table is the sum of TKN, nitrite and nitrate

[c]The value of 70 is only for suitable areas for aquaculture and exploitation of benthic resources

[d]Aquifers with high vulnerability

[e]Aquifers with low vulnerability

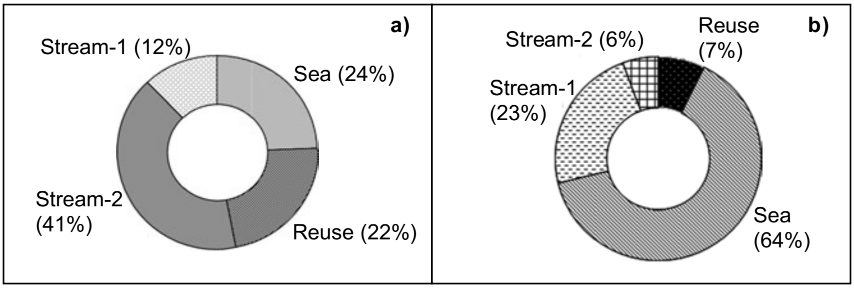


Fig. 19.3 Final destination of effluents from centralized WWTPs in the Atacama Desert. (**a**) Proportion in quantity of WWTPs; (**b**) Proportion in flow. (Data source: Vera-Puerto et al. [11] and SISS [20])

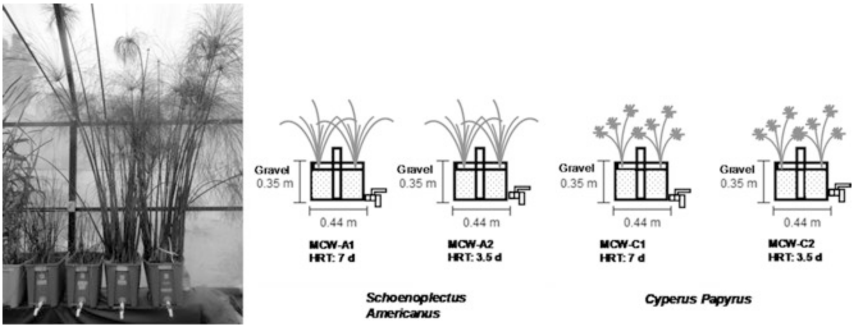


Fig. 19.4 First experimental setup for subsurface treatment wetlands. Left: photography of the treatment system at month 4. Right: representation of the experimental set up

19.3 Experimental Development by CIDERH-UNAP

19.3.1 Experimental Treatment Wetlands on the Coastal of the Atacama Desert

The CIDERH Experimental Unit for the development of experiments with TWs is located in the Pacific coastal city of Iquique (northern Chile) inside the Atacama Desert, in the administrative Region of Tarapacá. The climate in this area is characterized by being one of the most arid cities in the world, with minimal rainfall (typically less than 5 mm/year) but abundant cloudiness. The mean solar radiation is between 150 and 250 W/m^2, the relative humidity ranges from 55% to 90%, and the windspeed averages at approximately 0.6 m/s [25]. The experimental setup is separated from outdoor conditions using an anti-aphid mesh to protect the plants from insects.

The first experiments were developed using subsurface treatment wetland fed in batch mode to evaluate the influence of plants on effluent quality. Figure 19.4 shows the experimental setup. Each TW was constructed from a 30-L plastic unit (0.44 m × 0.30 m × 0.35 m; length × width × height). The TWs were filled with Ø 19 mm gravel up to a depth of 0.30 m. The plants were classified into two groups: native plants (denoted "A") and foreign plants (denoted "C"). Three plant species in group A were used: *Festuca orthophylla* and *Cortaderia atacamensis*, for the first 3 months (showing adaptation problems), and *Schoenoplectus americanus* from the fourth month to the end. One species was used from group C (*Cyperus Papyrus*) [19].

The second noteworthy objective of this experiment addressed hydraulic retention time (HRT). As indicated by Fig. 19.4, two HRTs were exercised: 7 d denoted "1", and 3.5 d, denoted "2". The aim of varying HRT was focused on researching the effect of increasing HRT on effluent quality (nutrient and salinity conditions) and water loss.

The experiment was conducted over the course of 7 months. The first month was for the adaptation and startup of the system while, monitoring time was over the final 6 months. Water quality parameters such as pH, temperature, electrical conductivity (EC), and oxidation-reduction potential (ORP) were measured using calibrated electrodes (Portable Multiparameter Hanna HI9829). Other parameters including chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4^+-N), nitrate (NO_3^--N), total phosphorus (TP), phosphate (PO_4^{-3}-P) and fecal coliforms (FC) were measured photometrically by a multiparameter photometer for municipal wastewater (HANNA HI- 83214) using reagent test kits based on procedures from APHA-AWWA-WEF [26]. Finally, total suspended solids (TSS) were measured following APHA-AWWA-WEF [26]. These water quality parameters were measured for both influents and effluents.

Figure 19.5 shows the results of the water quality in the effluents and Table 19.4 shows the associated removal efficiencies. According to Vera et al. [18], and taking into account the results in Fig. 19.5 and Table 19.4, it was determined that there was a significant positive influence ($\alpha < 0.05$) of above 30% for the removal of TN, NH_4^+-N, TP, and PO_4^{-3}-P by *Cyperus papyrus* for HRT2 (3.5 d). While this significant positive influence ($\alpha < 0.05$) was maintained for HRT1 (7 d), but the removal of TN, NH_4^+-N, TP, PO_4^{-3}-P increases by more than 50%. However, the increase was only 5% for COD [19]. This influence could be explained by the vigorous growth of *Cyperus papyrus* under the hyper-arid conditions of this experiment compared to *Schoenoplectus americanus*.

In the case of HRT, a significant positive influence ($\alpha < 0.05$) of greater than 10% was determined for MCW planted with native species *(Festuca orthopylla, Cortaderia atacamensis and Schoenoplectus americanus)* in removing COD, TN, NH_4^+-N, TP, and PO_4^{-3}-P. This result is the same for MCW planted with *Cyperus papyrus,* where the HRT had a significant positive influence ($\alpha < 0.05$) of more than 10% in removing TSS, TN, NH_4^+-N, TP, and PO_4^{-3}-P. N-Nitrate was not found in the effluents, indicating that nitrification was not developed in any of the evaluated treatment wetlands. This result is consistent with ORP values below −200 mV [19], which shows that the MCWs evaluated did not have sufficient conditions for nitrification processes, and anerobic routes were the most important for reducing organic matter.

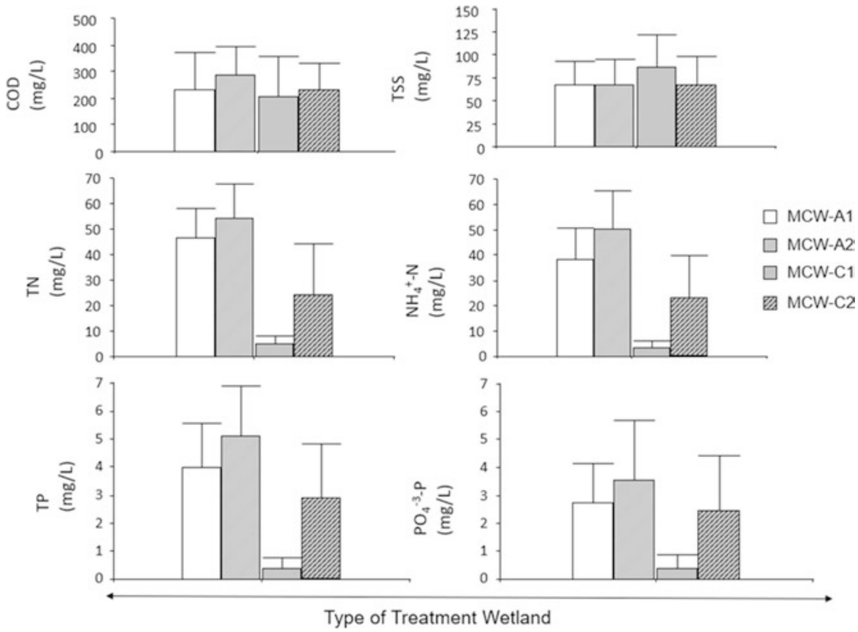


Fig. 19.5 Effluent water quality for first experimental treatment wetlands [19]

Table 19.4 Removal efficiencies (in percentage) by TW [19]

Parameter	TW (average ± standard deviation) (%)			
	MCW-A1	MCW-A2	MCW-C1	MCW-C2
COD	58 ± 17	47 ± 13	62 ± 20	58 ± 11
TSS	47 ± 20	24 ± 4	21 ± 2	19 ± 11
TN	29 ± 14	17 ± 16	92 ± 7	61 ± 31
NH_4^+-N	32 ± 13	12 ± 11	93 ± 7	54 ± 34
TP	37 ± 14	17 ± 11	93 ± 8	54 ± 23
PO_4^{-3}-P	28 ± 17	17 ± 13	92 ± 6	48 ± 26
FC[a]	2.1 ± 1.2	1.8 ± 1.3	2.8 ± 1.0	2.0 ± 1.1

[a]Removal is expressed in reduction of Log Units (Log MPN/100 ml)

Finally, other important results of this experiment were related to the loss of water and its effect on effluent salinity. According to Vera et al. [19], when native plants were used, the water loss (regardless of HRT) was always below 25%. However, when foreign plants such as *Cyperus papyrus* were used, the water loss was between 30% and 75%. This result demonstrates that native plants adapted to this arid environment could result in less water flow loss in effluents, increasing the amount of water that can be reused as irrigation water. Regarding the effects on effluent salinity, the experiment shows several important aspects. First, the linear relationship between water loss and EC increased. Second, when water loss was below 23% (which includes more than 95% of the data for native plants), the non-significant effect ($\alpha > 0.05$) on the EC value in effluents was observed [19]. This is important when water reuse in irrigation activities is considered for reusing effluents. More details about this first experimental system can be found in Vera et al. [19].

The second experiments focused on studying the performance of vertical subsurface flow treatment wetlands (VTWs) in the coastal region of the Atacama Desert. Accordingly, nine experimental units were built. All VTWs were constructed from 0.2 m PVC pipes, and their dimensions and materials are shown in detail in Fig. 19.6. This experiment focused on: (a) studying the influence of ornamental plants on wastewater treatment, and (b) reducing the height and replacing the medium (using zeolite instead of sand) in VTWs. *Zantedeschia aethiopica* was used as the experimental ornamental plant, given its potential for use in tropical and subtropical climates [27]. *Schoenoplectus californicus* was used as a control plant species, given beneficial previous experimental results in Chile [28, 29].

The VTWs were fed with screened wastewater from the Barrio Industrial WWTP in the city of Iquique (Chile). The water was diluted to 30% to simulate the effluent from a septic tank. The VTWs were operated for 6 months with monitoring taking place in the last 5 months. The hydraulic loading rate (HLR) was 120 mm/day applied by 12 pulses/day. The application strategy was defined with periods of rest and operation, with each VTW operating for 5 d and resting for 10 d similar to that suggested by Stefanakis et al. [30].

Figure 19.7 presents the average water quality in the effluents, while Table 19.5 shows the associated removal efficiencies.

The results in Fig. 19.7 shows similarities for all water quality parameters evaluated for the different VTWs (Fig. 19.6), demonstrating that the effluents concentration for COD and TSS (including standard deviation) were always below 80 mg/L and 30 mg/L, respectively. This confirms sufficient removal, above 50% and 80%, for COD and TSS, respectively, by all the VTWs evaluated in this work.

In the case of nitrogen, the results demonstrated a very good nitrification, where NH_4^+-N effluent concentration was always below 1.5 mg/L with removal efficiencies higher than 90% for all VTWs and reflected in production of NO_3^--N. Despite nitrate production, TN removal exhibited efficiencies of approximately 40%, while, TP removal exhibited efficiencies greater than 70%. In both cases, these removal efficiencies can be considered high for single stage TWs [31, 32]. Nutrient removal achieved in this experiment can be explained by the development of the plants. In the case of *Schoenoplectus californicus*, the plants reached a height of approximately 0.6 m with 22 leaves at the end of the experimental timeline, while *Zantedeschia aethiopica* reached a height of approximately 0.30 m with up to 20 leaves. Furthermore, the results obtained with the plants suggested an adaptation to the arid environment, especially by *Zantedeschia aethiopica,* but this plant can increase up to 0.6 m its height. Despite the development of *Zantedeschia aethiopica,* its leaves presented necrosis problems at the tips, as shown in Fig. 19.8. The necrosis could be a consequence of salinity (EC > 1.500 μS/cm, Table 19.2) and unbalance supply between NO_3^--N/NH_4^+-N in the wastewater. In addition, the

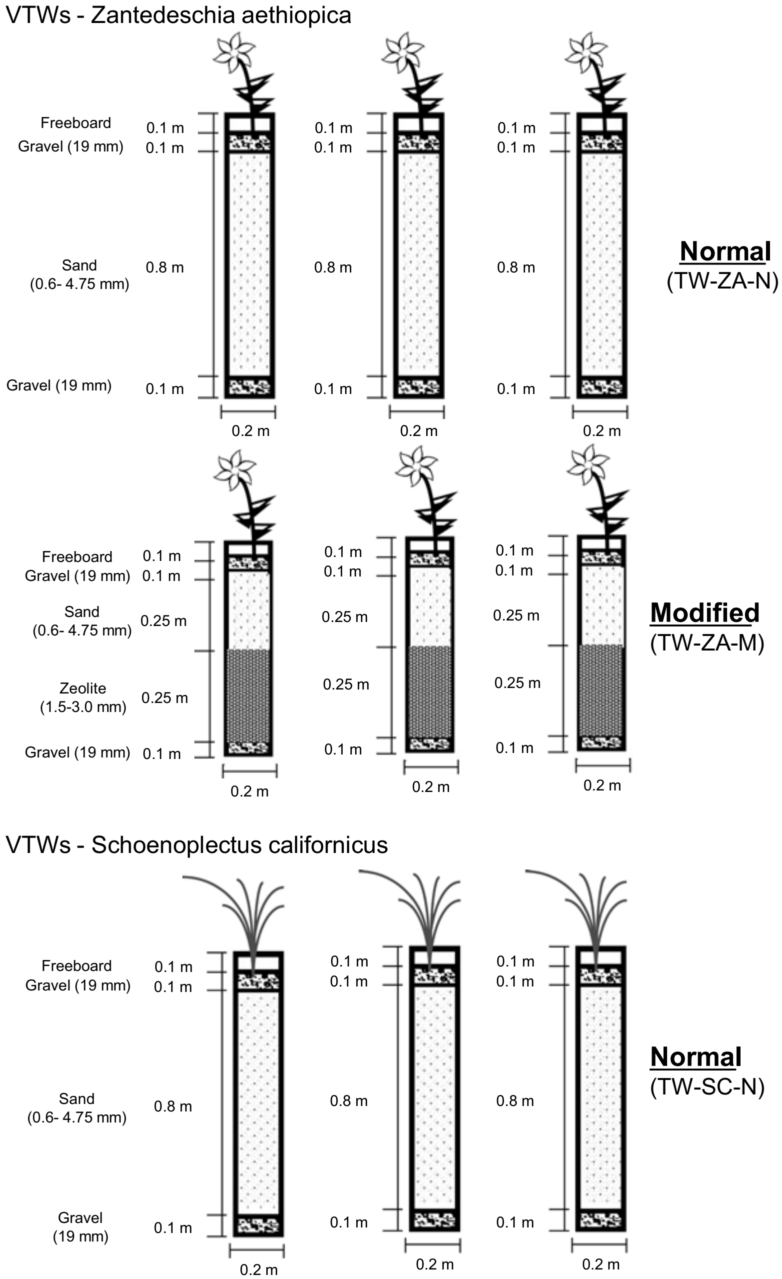


Fig. 19.6 Second experimental setup. Vertical Subsurface Flow Treatment Wetlands (VTWs)

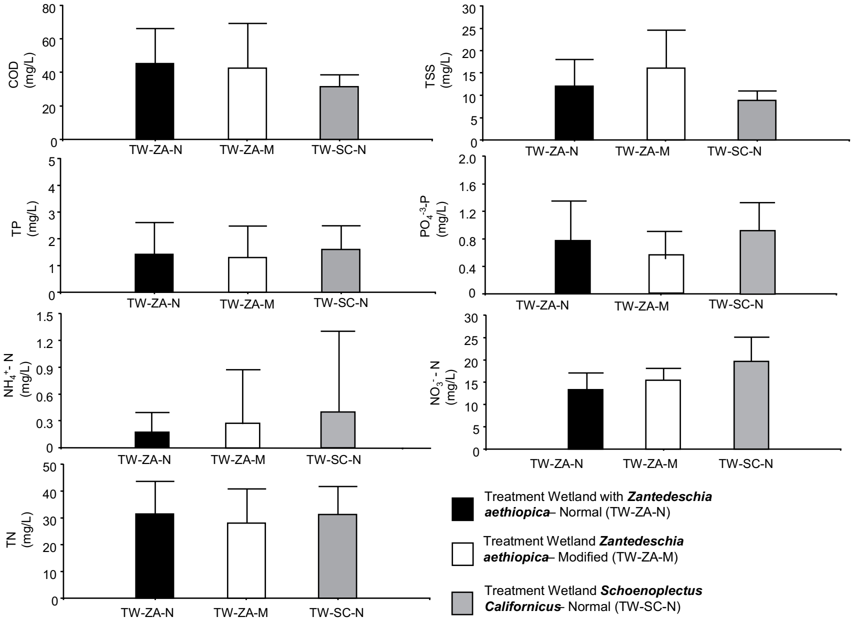


Fig. 19.7 Effluent quality for the second experimental setup, VTWs

Table 19.5 Removal efficiencies (in percentage) by TW

Parameter	Treatment wetland (average ± standard deviation) (%)		
	TW-ZA-N	TW-ZA-M	TW-SC-N
COD	69 ± 8	56 ± 25	77 ± 10
TSS	92 ± 6	84 ± 22	95 ± 3
TN	40 ± 11	47 ± 9	50 ± 7
NH_4^+-N	99 ± 1	99 ± 1	99 ± 1
TP	81 ± 14	73 ± 22	72 ± 9
PO_4^{-3}-P	81 ± 15	73 ± 22	72 ± 11
FC[a]	4.7 ± 2.5	4.1 ± 2.6	4.7 ± 2.5

[a]Removal is expressed in reduction of Log Units (Log MPN/100 ml)

positive increase in nutrient removal could not be achieved in the modified VTWs where Chilean natural zeolite was added, a material characterized by the potential removal of phosphorus and ammonium as a support medium in treatment wetlands [33]. It is possible that a bottom saturation of modified VTWs can increase contact time between the wastewater and the zeolite, increasing the adsorption of phosphate and ammonium, and consequently, increasing the efficiency of nitrogen and phosphorus removal [34, 35].

These preliminary results achieved with the VTWs using ornamental plants in the Atacama Desert demonstrate the possibility of 30% reduction in height

Fig. 19.8 View of *Zantedeschia aethiopica* in Normal VTW

compared to traditional VTWs (for example Danish guidelines, Brix and Arias [31]). For now, the experimental study continues for another year.

19.3.2 Effluent Reuse: Aeroponic Cultivation Systems

Atacama Desert soil can reach salinity values up to 65 dS/m [36, 37], rendering it unsustainable for agriculture activities. Thus, the use of soilless cultivation techniques has been proposed as an alternative to traditional cultivation systems to promote the reuse of effluents in the irrigation of agricultural products in the Atacama Desert. Accordingly, the CIDERH team has experimented with a soilless cultivation technic-aeroponics. An aeroponic growing system is one in which the roots develop in the air and are subjected to an inert medium within a closed, dark, and controlled environment saturated with moisture and nutrients [11, 38, 39]. This cultivation technique has been demonstrated to be safe (without contact between water, products, and operators) and efficient in the use of water resources similar to other soilless cultivation techniques [40].

As a first experiment, effluents from mesocosm treatment wetlands (MTW) fed in batch were used as irrigation water (described earlier in this book chapter). Two experimental aeroponics units (A and B) were built from 96-l cubic plastic tanks of 0.60 m × 0.4 m × 0.4 m (length × width × height) in the CIDERH experimental Unit (Iquique, Chile). Each experimental unit was equipped with eight places to hold planted baskets (plant density: 33 plant/m^2). Each planted basket was slotted with a volume of 232.26 cm^3 (height 8 cm; upper diameter 8 cm; lower diameter 6 cm) and filled with Arlite (8–16 mm diameter). Arlite was employed as a support material for the root system of the plant as it allows root aeration and water retention during and after irrigation [11]. The aerial part of the plant was allowed to develop freely in the experimental unit. The irrigation was carried out with micro jets, fed with a pump for each experimental unit. The experimentation was performed through farming Lily Tresor, a cut flower plant widely sold in the Chilean market that is sustainable for soilless culture and tolerant to saline conditions (EC, 2.300 μs/cm). This saline condition is commonly found in municipal wastewater in arid environments [11].

Unit A was irrigated with water composed of an equivalent mixture (50%) of effluents from the two treatment wetlands planted with native plants, *Schoenoplectus americanus*. Meanwhile, unit B was also irrigated with water composed of an equivalent mixture (50%) of effluents from the two treatment wetlands planted with *Cyperus papyrus*, a non-native plant from to the Atacama Desert [41]. The effluents employed as irrigation water corresponded to effluents of months 4–7, during operation of the treatment wetlands (described previously). Figure 19.9 shows the different photographs of the evolution of Lily Tresor in the two experimental aeroponics units and a bar chart displaying height evolution for the two experimental units.

The average height for Lily Tresor at harvest (week 9–10) for the two units varied between 0.50 and 0.6 m, with non-significant differences ($\alpha > 0.05$) between the two units [41]. It is important to note that height values greater than 0.65 m are considered for export, but lower values are considered for national markets [42]. Thus, the heights obtained in this first experiment would indicate that the flowers produced could only be sold in national markets. According to Vera-Puerto et al. [11], the main factor responsible for this height problem is light intensity, since values up to 120 K lux can be measured in the coastal region of the Atacama Desert. Other factors (such as water salinity and relative humidity) were identified as important for managing in future applications such as for industrial production. In addition, necrosis problems at the leaves in the bottom part of the plants were detected. In similar way than plants of Zantedeschia, the necrosis could be associated to water salinity (above 1500 μS/cm).

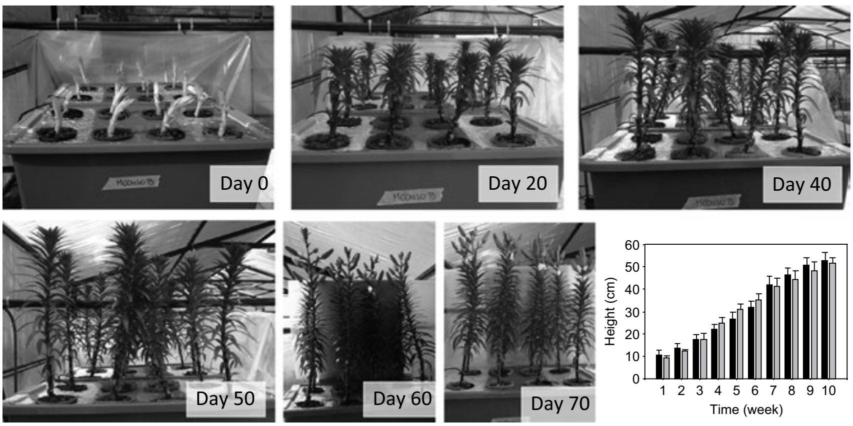


Fig. 19.9 Evolution of the cultivation system for the two experimental units: (■) Unit A; (□) Unit B

As result of the first experiment, a pilot scale experiment consisting of 192 m^2 passive greenhouse was installed at the "Pampa del Tamarugal" (locality of Pozo Almonte, Region of Tarapacá, Chile), 55 km from Iquique with the support of "Fundación para la Innovación Agraria" of the Ministry of Agriculture of Chile. In the greenhouse, aeroponic beds of 6 m × 1 m × 1 m (length × width × height) were built with a production capacity of 3600 plants of densities between 64 and 100 bulbs per m^2. The use of a greenhouse was necessary to control Pampa del Tamarugal extreme conditions, where the respective average temperature and relative humidity are 1.1–29.9 °C and 17.5–80.2%, during the autumn-winter season, and 7.6–31.9 °C and 20.7–80.3%, for the spring-summer season. In the pilot scale experiment, different varieties of Lily (such as Original Love, Golden Tycoon, Ravello, Litouwen, Advantage, and Montebello) were cultivated. Secondary effluents with disinfection from the WWTP of Pozo Almonte were used as irrigation water. The Pozo Almonte WWTP is composed of a dosing chamber, an aerated pond, a sedimentation pond, and final, disinfection by chlorine. The effluents from this WWTP meet the Chilean Regulations shown in Table 19.3, with exceptions related with boron, chlorides, and sulphate, which is typical in the wastewater produced in the Pampa del Tamarugal (interior of Atacama Desert). Control of light intensity to 20 K lux was obtained with shading meshes of between 50% and 75%. It is important to remark that light intensity values between 67 and 200 K lux were measured outside the greenhouse at midday; therefore, shading through any systems is mandatory to increase stem height in the Lily varieties cultivated in the Atacama Desert.

As a result of this pilot scale experiment, between 70% and 80% of commercial quality flowers were obtained, with stem lengths between 70 and 80 cm. For the autumn-winter and spring-summer cycles, crop cycle production varied between 70 and 90 d in duration for both seasons evaluated. Figure 19.10 illustrates the crop development through pictures taken at different times, including a table with values for average stem and inflorescence length at harvest for the different varieties of Lily used in this pilot scale experiment. More details about this experimental system can be found in Olave et al. [43].

19.4 Conclusions

This book chapter reported information pertaining to the Atacama Desert in Chile (climate, water use, and policies) as well as experience with experimental systems (treatment and reuse) focused on the development of the treatment wetland as an alternative technology for the treatment of wastewater in this particular environment. The results show that despite treatment coverage in urban areas being nearly 100%, less than 10% of the wastewater produced is reused. However, specific information regarding treatment and reuse for rural areas could not be displayed due to a lack of current governmental and scientific information. This is an important topic because the Atacama Desert occupies 40% of the Chile national territory and has several rural small towns far from each other where investments in centralized water

Lily variety	Length (average) (cm)	
	Stem	Inflorescence
Original Love	80.8	13.2
Golden Tycoon	70.5	13.0
Ravello	67.9	12.2
Litouwen	79.4	12.3
Advantage	77.4	14.0
Montebello	74.3	10.6

Fig. 19.10 Evolution of the Lily crop in the pilot scale experiment developed at the Pampa del Tamarugal

treatment plants are not feasible. Therefore, treatment wetlands are presented as a technological alternative to promote the social and economic development of this vast territory and its communities.

The results of both studies presented here demonstrate its feasibility of application. In the first case, the experiment carried out in the CIDERH Unit showed that different plant species (native, foreign, and ornamental) can be applied in TWs within the coastal region of the Atacama Desert. In addition, the experiments showed that WWTP effluents, especially when vertical treatment wetlands were applied, have potential to be used as irrigation water for agricultural activities. However, due to the salinity conditions of soils in the Atacama Desert, alternative cultivation technics could be used with aeroponics being the technique discussed in the book chapter. Based on this cultivation technique, the results of the experiments showed that in the first approach (lab scale), the use of effluents from treatment wetlands as irrigation water allowed Lily Tresor to grow as a cut flower. However, due to the size obtained (under 0.65 m) under our protocol, the flowers could only be offered for national markets.

In the second approach (pilot scale), using effluents from an actual WWTP as irrigation water, different varieties of Lily reached heights between 70 and 80 cm. This demonstrated that the management of luminosity (with values lower than 20 K lux), was vital for improving of the height of cut flowers. Finally, all results of this book chapter show the range of possibilities that treatment wetlands have in the Atacama Desert and the need for more research on the adaptation of this technology in this extreme environment (in conjunction with reuse alternatives). This final issue (reuse) becomes relevant in a territory where more than 90% of drinking water is obtained from underground reservoirs, its demand competes with mining and agriculture activities, and most of the wastewater exits to the ocean through submarine outfalls.

Acknowledgments The authors wish to express their gratitude to Agencia Nacional de Investigación of Chile (ANID) for Grants No. ANID/REGIONAL/CIDERH/R09I1001 ANID/MEC/PAI/80170068 and ANID/FONDECYT/11180672, for supporting various experiments and results included in this book chapter. In addition, to Fundación para la Innovación Agraria from the Ministry of Agriculture of Chile for supporting the reuse pilot scale experimentation through Grant No. PYT 2015-0171 developed in collaboration with Nayra-Inti Indigenous Association and Aguas del Altiplano. Binita Gandhi would like to express their gratitude to the University of Victoria for permitting a virtual internship with Dr. Vera at Universidad Católica del Maule. The authors wish to express their gratitude to different people that took data shown in this book chapter through a thesis supported by CIDERH: Nataly Verdejo, Joyce Escobar, Mónica Galarce, Carolina Rojas, and the staff of CIDERH and Universidad Arturo Prat, that also supported the experimental construction and data taking for this book chapter: Verónica Ortiz, Yesenia Saavedra, Matías Sánchez, Christian Santander, Wladimir Chávez, Betzabe Torres, Oscar González, Sussy Tapia, Viviana Varas, Jose Aguilera, Paulina Galvez, Yerka Mamani and Elsa Mamani. Finally, the authors would like to recognize the support of Aguas del Altiplano (water company in Region of Tarapacá) for the different initiatives related to wastewater treatment and reuse promoted by CIDERH, with special mention to Sergio Fuentes, Renzo Aravena, Isabell Tello, Christian Barahona, Gastón Muñoz and Andrea Araos, for their important help and support.

References

1. Instituto Nacional de Estadística – Chile (INE) (2018) Síntesis de resultados Censo 2017. https://www.censo2017.cl/descargas/home/sintesis-de-resultados-censo2017.pdf. Accessed 30 Sept 2020
2. Köppen W (1884) Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet. Meteorol Z 1:215–226. https://doi.org/10.1127/0941-2948/2011/105
3. Rubel F, Kottek M (2011) Comments on: "the thermal zones of the Earth" by Wladimir Köppen (1884). Meteorol Z 20:361–365. https://doi.org/10.1127/0941-2948/2011/0258
4. Cereceda P, Larrain H, Osses P, Farías M, Egaña I (2008) The climate of the coast and fog zone in the Tarapacá Region, Atacama Desert, Chile. Atmos Res 87:301–311. https://doi.org/10.1016/j.atmosres.2007.11.011
5. Tully C, Rech J, Workman T, Santoro C, Capriles J, Gayo E, Latorre C (2019) In-stream wetland deposits, megadroughts, and cultural change in the northern Atacama Desert, Chile. Quat Res 9:63–80. https://doi.org/10.1017/qua.2018.122
6. Garreaud R, Rutllant J, Garreaud R, Rutllant J (2003) Coastal lows along the subtropical west coast of South America: numerical simulation of a typical case. Mon Weather Rev 131:891–908. https://doi.org/10.1175/1520-0493(2003)131<0891:CLATSW>2.0.CO;2

7. Houston J, Hartley A (2003) The central Andean west-slope rainshadow and its potential contribution to the origin of hyper-aridity in the Atacama Desert. Int J Climatol 23:1453–1464. https://doi.org/10.1002/joc.938
8. Universidad de la Frontera (UFRO) (2019) Coberturas SIG de Chile. Laboratorio de Geografía. http://labgeo.ufro.cl/catalogos/chile.html. Accesed 30 Sept 2020
9. Houston J (2006) Variability of precipitation in the Atacama Desert: its causes and hydrological impact. Int J Climatol 26:2181–2198. https://doi.org/10.1002/joc
10. Ritter B, Wennrich V, Medialdea A, Brill D, King G, Schneiderwind S, Niemann K, Fernández-Galego E, Diederich J, Rolf C, Bao R, Melles M, Dunai T (2019) Climatic fluctuations in the hyperarid core of the Atacama Desert during the past 215 ka. Sci Rep 9:1–13. https://doi.org/10.1038/s41598-019-41743-8
11. Vera-Puerto I, Olave J, Tapia S, Chávez W (2019) Atacama Desert: water resources and reuse of municipal wastewater in irrigation of cut flower aeroponic cultivation system (first laboratory experiments). Desalin Water Treat 150:73–83. https://doi.org/10.5004/dwt.2019.23612
12. Dirección General de Aguas (DGA) (2016) Atlas del Agua, Chile. Ministerio de Obras Públicas, Santiago. http://biblioteca.digital.gob.cl/handle/123456789/1382. Accesed 30 Sept 2020
13. Henze M, Harremoes P, Jansen J, Arvin E (2002) Wastewater treatment: biological and chemical processes. Springer, Heidelberg
14. Albalawneh A, Chang T, Chou C, Naoum S (2016) Efficiency of a horizontal sub-surface flow constructed wetland treatment system in an arid area. Water 8:1–14. https://doi.org/10.3390/w8020051
15. Araya F, Vera I, Sáez K, Vidal G (2016) Effects of aeration and natural zeolite on ammonium removal during the treatment of sewage by mesocosm-scale constructed wetlands. Environ Technol 37:1811–1820. https://doi.org/10.1080/09593330.2015.1133715
16. Superintendencia de Servicios Sanitarios (SISS) (2019) Informe de gestión del sector sanitario, Chile. https://www.siss.gob.cl/586/articles-17722_recurso_1.pdf. Accessed 30 Sept 2020
17. Villaroel L (2012) Asociaciones comunitarias de agua potable rural en Chile: diagnóstico y desafíos. https://www.cooamel.cl/documentos/agua_potable/Asociaciones-comunitarias-de-agua-potable-rural-en-chile.pdf. Accessed 30 Sept 2020
18. Ministerio de Obras Públicas (MOP) (2020) Mesa Nacional del Agua, Primer Informe. https://www.mop.cl/Prensa/Documents/Mesa_Nacional_del_Agua_2020_Primer_Informe_Enero.pdf. Accessed 30 Sept 2020
19. Vera I, Verdejo N, Chávez W, Jorquera C, Olave J (2016) Influence of hydraulic retention time and plant species on performance of mesocosm subsurface constructed wetlands during municipal wastewater treatment in super-arid areas. J Environ Sci Heal Part A 51:105–113. https://doi.org/10.1080/10934529.2015.1087732
20. Superintendencia de Servicios Sanitarios (SISS) (2020) Resultados fiscalización de Plantas de Tratamiento de Aguas Servidas, Chile. https://www.siss.gob.cl/586/w3-propertyvalue-6408.html. Accessed 30 Sept 2020
21. Biblioteca del Congreso Nacional de Chile (BCN) (2000) Decreto Supremo 90 de 2000. Establece norma de emisión para la regulación de contaminantes asociados a las descargas de residuos líquidos a aguas marinas y continentales superficiales. https://www.bcn.cl/leychile/navegar?idNorma=182637. Accessed 30 Sept 2020
22. Vera I, Jorquera C, López D, Vidal G (2016) Humedales construidos para tratamiento y reúso de aguas servidas en Chile: reflexiones. Tecnol Cienc Agua 7:19–35
23. Instituto Nacional de Normalización (INN) (1987) Norma Chilena (NCh) 1333 Of. 78 modificada 1987. Requisitos de calidad del agua para diferentes usos. Santiago de Chile
24. Biblioteca del Congreso Nacional de Chile (BCN) (2003) Decreto Supremo 46 de 2002. Establece norma de emisión de residuos líquidos a aguas subterráneas. https://www.bcn.cl/leychile/navegar?idNorma=206883. Accessed 30 Sept 2020
25. Arenas J (2020) Serie de informes Agrometeorológicos Campus Huayquique, Universidad Arturo Prat. Personal communication

26. American Public Health Association (APHA), American Water Works Association (AWWA), Water Environment Federation (WEF) (2012) Standard methods for the examination of water and wastewater, 22rd edn. Washington, DC
27. Zurita F, De Anda J, Belmont M (2009) Treatment of domestic wastewater and production of commercial flowers in vertical and horizontal subsurface-flow constructed wetlands. Ecol Eng 35:861–869. https://doi.org/10.1016/j.ecoleng.2008.12.026
28. Vera I, Araya F, Andrés E, Sáez K, Vidal G (2014) Enhanced phosphorus removal from sewage in mesocosm-scale constructed wetland using zeolite as medium and artificial aeration. Environ Technol 35:1639–1649. https://doi.org/10.1080/09593330.2013.877984
29. López D, Fuenzalida D, Vera I, Rojas K, Vidal G (2015) Relationship between the removal of organic matter and the production of methane in subsurface flow constructed wetlands designed for wastewater treatment. Ecol Eng 83:296–304. https://doi.org/10.1016/j.ecoleng.2015.06.037
30. Stefanakis A, Akratos C, Tsihrintzis V (2014) Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment, 1st edn. Elsevier, Amsterdam
31. Brix H, Arias C (2005) The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines. Ecol Eng 25:491–500. https://doi.org/10.1016/j.ecoleng.2005.07.009
32. Bohórquez E, Paredes D, Arias C (2017) Vertical flow-constructed wetlands for domestic wastewater treatment under tropical conditions: effect of different design and operational parameters. Environ Technol 38:199–208. https://doi.org/10.1080/09593330.2016.1230650
33. Vera-Puerto I, Saravia M, Olave J, Arias C, Alarcon E, Valdes H (2020) Potential application of Chilean natural zeolite as a support medium in treatment wetlands for removing ammonium and phosphate from wastewater. Water 12:1156. https://doi.org/10.3390/w12041156
34. Silveira D, Belli Filho P, Philippi L, Kim B, Molle P (2015) Influence of partial saturation on total nitrogen removal in a single-stage French constructed wetland treating raw domestic wastewater. Ecol Eng 77:257–264. https://doi.org/10.1016/j.ecoleng.2015.01.040
35. Pelissari C, Ávila C, Trein C, García J, de Armas R, Sezerino P (2017) Nitrogen transforming bacteria within a full-scale partially saturated vertical subsurface flow constructed wetland treating urban wastewater. Sci Total Environ 574:390–399. https://doi.org/10.1016/j.scitotenv.2016.08.207
36. Cáceres L, Delatorre J, De la Riva F, Monardes V (2003) Greening of arid cities by residual water reuse: a multidisciplinary project in northern Chile. Ambio 32:264–268. https://doi.org/10.1639/0044-7447
37. Tapia Y, Diaz O, Pizarro C, Segura R, Vines M, Zúñiga G, Moreno-Jiménez E (2013) Atriplex atacamensis and Atriplex halimus resist as contamination in pre-Andean soils (northern Chile). Sci Total Environ 450-451:188–196. https://doi.org/10.1016/j.scitotenv.2013.02.021
38. Buckseth T, Sharma A, Pandey K, Singh B, Muthuraj R (2016) Methods of pre-basic seed potato production with special reference to aeroponics—a review. Sci Hortic 204:79–87. https://doi.org/10.1016/j.scienta.2016.03.041
39. Lakhiar I, Gao J, Syed T, Chandio F, Buttar N (2018) Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. J Plant Interact 13:338–352. https://doi.org/10.1080/17429145.2018.1472308
40. Treftz C, Omaye S (2016) Hydroponics: potential for augmenting sustainable food production in non-arable regions. Nutr Food Sci 46:672–684. https://doi.org/10.1108/NFS-10-2015-0118
41. Vera-Puerto I, Olave-Vera J, Tapia S, Chavez W, Arias C (2020) Treated municipal wastewater reuse coming from constructed wetlands for cut flowers irrigation in aeroponic cultivation. Ing Univ 24(1-13):10.11144/Javeriana.iued24.tmwr
42. Auzaque-Rodríguez O, Balaguera-López H, Álvarez-Herrera J, Fischer G (2009) Efecto de la vernalización de bulbos reutilizados sobre la calidad de la flor de lirio (Lilium sp.) en la Sabana de Bogotá. Agron Colomb 27:65–71
43. Olave J, Torres B, Chavez W, Gonzalez O (2016) Producción de Lilium bajo invernadero en un sistema aeropónico recirculante con agua residual urbana tratada en el desierto de Atacama. https://www.opia.cl/601/w3-article-3500.html. Accessed 30 Sept 2020

Chapter 20
Wastewater Gardens Systems in Yucatan, Mexico; Northwest Australia; Northern Algeria and Southern Iraq

Mark Nelson, Florence Cattin, Davide Tocchetto, and Lamine Hafouda

Abstract Wastewater Gardens (WWG) systems are complete wastewater treatment plants (STP or WTP) using high biodiversity subsurface flow constructed wetlands (CW). Our work began in Biosphere 2, where CW completed water cycles, returned nutrients to fertile farm soil, produced fodder and habitat. Since, the WWG approach has been applied in 15 countries including Mexico, Australia, Algeria and Iraq, hot and arid areas with limited freshwater resources. These systems offer far less expensive, yet reliable, productive and longer-lasting treatment plants than so-called conventional centralized treatment plants, often disabled by challenging climates or extreme weather events and completely dependent on external power sources such as electricity. Over 30 WWG systems along the limestone Mexican Yucatan coast protect coral reefs from sewage pollution. In the remote northwest Australian Kimberley region, a series of WWGs improved sewage treatment, community hygiene and landscape beauty in indigenous communities. The WWG team implemented Algeria's first CW system in Tamacine, a pilot that served as a basis for further large-scale systems countrywide. "Eden in Iraq" Wastewater Gardens Project is in pre-implementation phase to provide the first effective sewage treatment for Marsh Arab towns, preventing contamination and helping in the restoration of these ancient and historic marshes. WWGs provide landscape beauty without additional water use, perform well in extreme climatic conditions and are valued by the local communities for their simplicity, beauty and non-reliance on costly energy-intensive technologies.

M. Nelson (✉) · F. Cattin · D. Tocchetto
Institute of Ecotechnics, US/UK, Santa Fe, NM, USA

Wastewater Gardens International, Santa Fe, NM, USA
e-mail: nelson@biospheres.com; fc@ecotechnics.edu; http://www.ecotechnics.edu; davide.tocchetto@libero.it; http://www.wastewatergardens.com

L. Hafouda
INRAA (Institut National de la Recherche Agronomique d'Algérie), Oued Smar, Algeria

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_20

Keywords Sewage treatment · Wastewater gardens · Nature-based solution · Ecological system · Biodiversity · Constructed wetlands · Nutrient recycling · Biosphere 2 · Water · Wetland plants · Plant biodiversity · Landscape enrichment

20.1 Introduction

Constructed wetlands (CWs) for the treatment of wastewater are fairly simple technically engineered systems that imitate the functions that natural wetlands, the kidneys of the planet, achieve for the Earth's biospheric cycles, removing and making nutrients available in the water purification process. Wastewater Gardens systems (WWG) use CWs as secondary treatment systems and utilize a diversity of natural physical, chemical and biological mechanisms achieving treatment levels that often surpass conventional wastewater treatment systems. Applicable for small to large populations (from 3 people or 200+ L to 20,000+ m^3/day) they require significantly less capital expenditure, use no added chemicals and require far less machinery and energy – if at all – to implement and maintain than systems that are reliant on significant mechanical and/or chemical inputs (with the added pollution generated). From our experience and analysis of the literature, when properly designed and maintained, CWs are probably the most reliable and efficient wastewater treatment systems with their low operating and maintenance costs, flexibility and scalability, treatment levels, long-term resilience and vegetation production capacity at no extra needs of water as an added-value. While CWs alone will not make wastewater reach drinking water quality, they can easily combine with other technologies (i.e. membrane filtration, UV systems, and/or remaining within nature-based solutions, myco-remediation) to reach even higher treatment levels.

The principal feature of CWs, creating green zones without additional need of water, is even more valuable in hot and arid zones where water resources are scarce. The biodiversity and landscape enrichment that such ecosystems enable make them a useful tool for public policy makers and authorities involved in urban planning. From the production of flowers, fast-growing timber, fruit trees, fodder for animals, weaving materials and medicinal barks, for example, the further possibilities of turning CWs into vegetation production centers, and/or buffer zones areas are often much greater than currently implemented. The Wastewater Gardens International (WWG-I) team has repeatedly seen that the designed systems meet international standards for wastewater treatment, maintain effectiveness long-term with simple maintenance, and are able to function for at minimum several decades. They enhance the surrounding landscape, providing habitat and food for local wildlife, such as birds, butterflies, frogs and beneficial insects. WWG CWs systems have brought great satisfaction and have added to local beauty with their distinctive plant life.

Each treatment system is adapted to its site and its engineering calculated according to the quantity and type of wastewater being treated, desired output, reuse and climatic conditions, adapted to budget and local realities and material availability. The majority of the treatment plants use subsurface horizontal-flow CWs as secondary water treatment, though for larger applications we incorporate vertical-flow systems. WWG systems are generally gravity-flow systems for simplicity of design and maintenance and a great flexibility of configuration. The treated water after the CW is generally further used for landscaping via subsurface irrigation drainage trenches but can also be oriented to a pond system with fish.

In this chapter, we first present the origins of the WWG approach in the Biosphere 2 closed ecological system facility in southern Arizona. Then we discuss systems built in four hot and arid regions: Yucatan coast, Mexico; Kimberley region of northwest Australia; Tamacine, on the edge of the Sahara Desert, Ouargla Province, Algeria; and Marsh Arab towns in the southern Iraqi marshlands.

20.2 Case Studies

20.2.1 Biosphere 2, Southern Arizona, USA

In a small world, completing water and nutrient cycles are equally critical but easier to see than the vast biogeochemical cycles which keep resources available for maintaining life in the Earth's biosphere. Biosphere 2 was the world's first mini-biospheric materially closed ecological system and included five zones modeled on Earth's wilderness biomes, a farm and living spaces/laboratories for eight resident crew. It had an airtight footprint of 1.2 hectares, 200,000 m^3 volume and with relatively small buffers of atmosphere and ocean (4 million L supporting a coral reef), its internal cycles were greatly accelerated. In Biosphere 2, it was clear that recycling water and wastewater and their nutrients was key to achieving sustainability. So irrigation water draining through the farm and the other biomes ("leachate water") was reused for irrigation, mixed with condensate water and the treated human wastewater from the constructed wetlands. With a finite amount of materials, it becomes clear and necessary that everything must be re-used. There are no "wastes" in a closed ecological system but rather resources to be reutilized (Fig. 20.1) [1–4].

Biosphere 2's accelerated cycling times included its water cycle (Table 20.1). The CWs in Biosphere 2 were designed with the help of B.C. Wolverton of NASA and treated all human domestic wastewater, laboratory and workshop wastes and those of the domestic animals (chickens, pigs and goats). Comprising 41 m^2, these wetlands had over a dozen floating and emergent plant species and treated approximately 1 m^3 of wastewater daily. Its vegetation was harvested to feed domestic animals and treated effluent was returned to the farm irrigation supply, thus returning all water and nutrients to its soils. With 4 days pre-treatment in anaerobic tanks and 3 days residence in the wetlands, BOD was reduced by >75% and its operation ensured that water and nutrients were kept in biotic circulation [5, 6].

One of our authors' experience (MN) in Biosphere 2 managing and researching the CWs during the first two-year closure experiment inspired him to continue

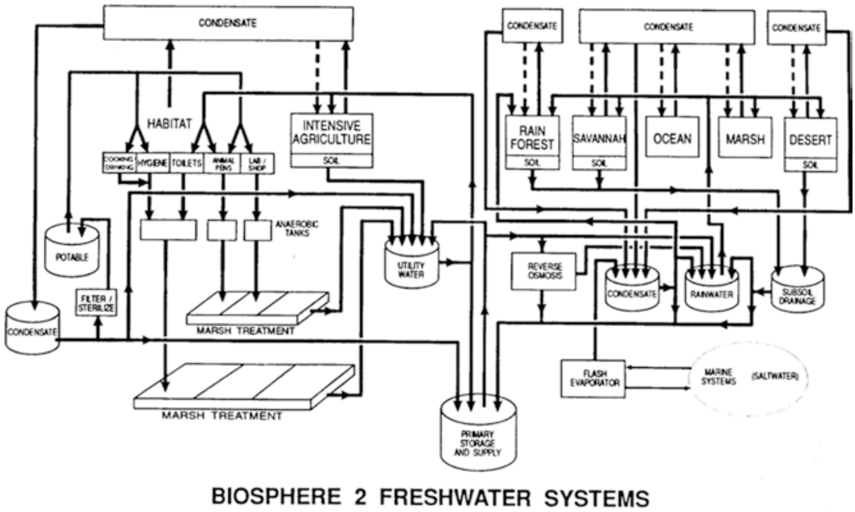


Fig. 20.1 Schematic showing the complex and interconnected systems recycling freshwater in Biosphere 2. Marsh treatment refers to the constructed wetland systems which returned both water and nutrients to the farm to maintain soil fertility

Table 20.1 Water fluxes and residence times compared between the Earth's biosphere and Biosphere 2 [7]

Reservoir	Earth residence time	Biosphere 2 estimated residence time	Acceleration compared to Earth
Atmosphere	9 days	~ 4 h	50–200 times
Ocean/ marsh	3000–3200 years	~ 1200 days (3.2 years)	1000 times
Soil water	30–60 days	~ 60 days	Similar

developing CWs as an ecological approach which treats wastewater as a resource rather than a toxic substance. Inside Biosphere 2, it was clear that there was "no away": that is, nowhere to dump or dispose of pollutants and wastes. The fallacy of earlier environmental engineers who proclaimed "the solution to pollution is dilution" becomes apparent and absurd in a small world, and is increasingly anachronistic in our planetary biosphere. While it is difficult to directly return water and nutrients contained in human wastewater to our agricultural soils, Biosphere 2 showed that high biodiversity CW systems which support beneficial insects and wildlife (e.g., ladybugs and frogs inside Biosphere 2) can be designed for effective treatment and productive use of its water and nutrients while enhancing landscape beauty.

20.2.2 Yucatan Peninsula, Mexico

The coastal Yucatan Peninsula offers unique challenges for wastewater treatment and reuse. Its tropical climate has an average temperature of around 26 °C. and though annual rainfall is over 1200 mm, most falls during the May/October wet season with the remaining 6 months averaging less than 70 mm. Its highly karst (limestone) geology means that wastewater quickly pollutes shallow groundwater tables and is transported to the ocean. Most "septic tanks" there were built without a bottom, creating a conduit for wastewater. Offshore are beautiful coral reefs, crucial to the region's ecotourism economy. Pollution of the nearshore marine environment is devastating to corals and other marine life. Saltwater intrusion makes potable water difficult to obtain: many communities import drinking water.

Yucatan conditions are similar to those in many areas (e.g., Kimberley, West Australia; Algeria and Iraq covered in later sections of this chapter), i.e., remote from large cities and technical infrastructure. Thus wastewater treatment that needs highly trained technical management and which heavily rely on inputs like reliable electricity, chemicals, spare parts etc. may perform well initially, but will degrade in efficiency over time. These areas are also subject to climatic extremes like violent storms, hurricanes, sandstorms or simply an inadequate infrastructure and economy to ensure reliable electrical service which are necessary to operate conventional sewage treatment plants. This adds to the advantages of constructed wetlands for these areas: reliable performance over decades, minimal or no need for electricity, maintenance requirements that are similar to those for other landscape/gardens rather than highly technical along with vastly lower operating costs.

Nelson developed the WWG approach while working with Prof. H.T. Odum, the father of ecological engineering, at the University of Florida's Center for Wetlands and with the support of the Biosphere Foundation. Invited by the Centro Ecologico Akumal to return to where Biosphere 2's corals had been collected to come up with solutions to the almost total lack of wastewater treatment, 30 WWG, subsurface flow CWs, were installed for houses, condominiums, restaurants and small hotels in the Akumal/Tulum coastal area south of Cancun from 1996 to 2002 (Fig. 20.2).

We tested using highly biodiverse plants for the WWGs, both native wetland and decorative and harvestable species valued in the area. Many of the plants which proved successful in the constructed wetlands were unpredicted as their ability to tolerate anaerobic growing conditions was not found in the literature but could tolerate the 3–5 ppt salinity of tap water in the area. Gravity flow was used for most systems, but to avoid excavation through hard limestone, some of the WWG systems were raised garden boxes with submersible pumps pumping from new sealed septic tanks to the wetlands. Locally sourced limestone gravel was used for the wetlands' media and may have increased phosphorus removal. Because geomembranes are expensive to import and labor costs are low in the Yucatan, local construction contractors built the WWGs using steel-reinforced concrete. The first two WWGs were studied and Table 20.2 presents their water quality data. Discharge water from the systems was sent to subsurface leach drains which supported

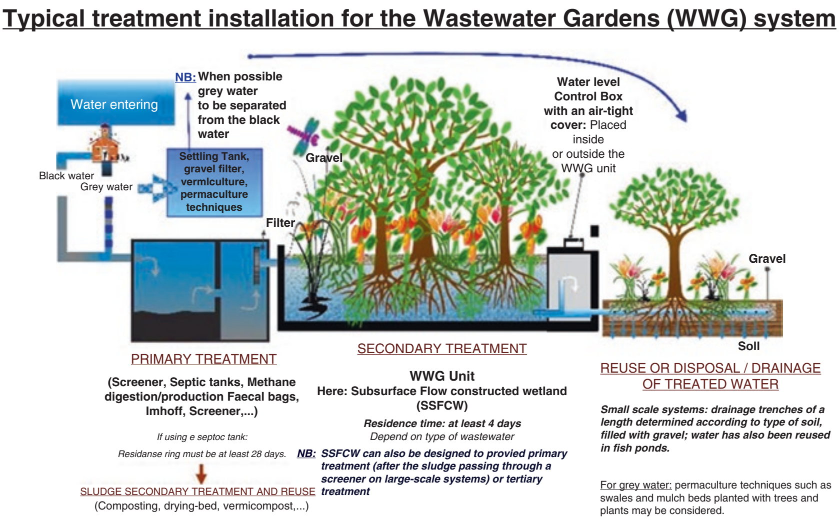


Fig. 20.2 Schematic of a Wastewater Garden system includes using the treated water for subsurface irrigation of additional landscape or productive plants/trees. (www.wastewatergardens.com) [8]

Table 20.2 Treatment efficiency of WWG subsurface flow CWs studied at two locations in the Yucatan, Mexico. The coliform bacteria reduction was without using chlorine or other disinfection methods [9, 10]

Parameter	In (septic tank) mg/L	Out (discharge WWG) mg/L	Removal %	Loading kg/ha/day
BOD5	145	17.6	87.9	32.1
Phosphorus (TP)	8.05	1.9	76.4	1.7
Nitrogen (TN)	47.6	10.0	79	10.3
Total suspended solids	69.9	38.9	44.4	15.1
Coliform bacteria	49×10^6	2.2×10^3	99.8	

additional green plants in the landscape. Not only were the systems competitive in price to conventional "package plant" treatment systems but the gardens created some of the most attractive gardens where they were installed (Figs. 20.3 and 20.4).

20.2.3 Kimberley Region, Northwest Australia

The Kimberley region of northwest West Australia is vast, covering over 400,000 km^2 (three times the size of England). The climate is characterized as hot monsoonal tropics. Rainfall varies, greater in its northern reaches (up to 1200 mm) and lessening with distance inland from its coasts (530 mm). But everywhere, the rain is 90%

Fig. 20.3 Yucatan coastal Wastewater Garden systems: (**a**) Xpu-Ha Ecopark beach restaurant (**b**) ecological field station, Akumal (**c**) house Akumal (**d**) WWG in front of Italian restaurant/resort, Tulum

Fig. 20.4 Photo of one of the first WWG systems in Akumal, Mexico after 20 years of operation. (Photo by Gonzalo Arcila) [8]

concentrated in a short summer wet season from mid-December to early April; the rest of the year can be virtually without precipitation. But temperatures average 27 °C. (81 °F.) and even in winter, mean maximum temperatures are above 30 °C., with a hot, dry 3-month period with mean maximum temperatures of 37 °C. The region also experiences extreme variability: from more than twice annual rainfall to years with only 25%. During the wet season, tropical cyclonic weather can produce rain events of 100–200 mm over a few days, leading to widespread flooding, making much of the region inaccessible and causing leach drains to fail and sewage to surface.

The region has low population including many Aboriginals living in remote communities. Problems with wastewater treatment include poor location of septic tanks and leach drains in land subject to wet season inundation, lack of maintenance and the high expense and malodor of sewage lagoons which have been installed in some Aboriginal communities.

Nelson's Institute of Ecotechnics (IE) has a long-term ecological project, Birdwood Downs, near Derby in the West Kimberley and familiarity with the problems of effective sewage treatment in the region. After initial work supported by the Biosphere Foundation, WWG-I was founded in 2004. Working with the other co-authors and regional representatives, WWGs were installed in 14 countries worldwide. In the Kimberley, WWG-I worked with Birdwood Downs to install pilot demonstration systems, concentrating on Aboriginal communities, under an agreement with the West Australian Department of Health which recognized that remote towns and indigenous communities were in urgent need of practical, decentralized solutions to sewage treatment and reuse. Many projects received financial support from the Aboriginal Housing division of the W.A. state government and Community Water Grants from the federal government.

Aboriginal community WWG projects began with meeting with the community to find out their problems with existing wastewater systems, their desires for green plants, flowers and fruit trees and to enlist their support. At Emu Creek where a number of Aboriginal artists live, they were paid to paint Dreamtime stories on Control Box lids to give them greater ownership of the systems (Fig. 20.5). Soil analyses and permeability tests were conducted and logistics for getting the materials and plants needed. After an initial pilot at Birdwood Downs, WWG systems

Fig. 20.5 (left) Community resident and artist Ned Johns with his Dreamtime painting on control box for his house's WWG system. (right) Another Control Box Dreamtime painting, Emu Creek community

were installed at the Emu Creek community (Kununurra, WA), Joy Springs (Fitzroy Crossing, WA) and Pandanus Park (Derby, WA) Aboriginal communities. The Birdwood Downs WWG had treatment efficiencies of 95% reduction of BOD and TSS, 48% reduction TN, 30% TP and 98.2% reduction of fecal coliforms without using disinfection. Results from the Emu Creek WWG were 89% reduction BOD, 90% TSS, 73% TN and 58% TP [8, 10].

Some of the problems the WWG installations had to solve included installing two small submersible pumps (one for backup) in the final Control Box to pump treated wastewater either to higher ground or the creation of "inverted leach drains" when wet season rainfall prevented gravity-flow to planted leach drains. Some of the installations used native plant ecoscapes in the final use area to ensure they would remain green without need of extra irrigation during the dry season (Fig. 20.6) [11]. The systems used geomembrane liners for sealing the CWs, at first polypropylene and then EPDM when it became available in West Australia. Ensuring ongoing maintenance, a persistent problem in outback Australia, has been an issue at some of the communities due to lapses and turnover in the service agencies that assist indigenous communities. But the WWGs were greatly appreciated for adding to the beauty of the communities and reducing health issues caused by septic tanks failures and plumbing backing up in houses and children playing in wet season

Fig. 20.6 Kimberley, West Australia WWG systems: upper left, peacocks enjoy the Birdwood Downs WWG; upper right: WWG for two houses at Emu Creek community; lower left: WWG for a house at Joy Springs; lower right: native plant/bush tucker ecoscape using the treated wastewater to further green the community in a leach drain of one of the WWGs at Pandanus Park

exposed sewage when previous leach drains failed which had been the case before the installation of the WWG systems.

20.2.4 Northern Sahara, Region of Touggourt, Tamacine, Algeria

The implementation of Algeria's first sewage water treatment plant (STP) using CWs and reuse of its treated water from April to June 2007 in the old Ksar of Tamacine by the Ministry of Water Resources resulted from a process started in 2004. The Tidjani family of Tamacine (Tamasîn) and world-known Algerian artist Rachid Koraïchi invited members of the IE to discuss appropriate ecological solutions and overall revitalization strategies for this area of the country's northeastern Touggourt province (Ouargla), on the northern edge of the Sahara desert.

This region's economy is almost exclusively based on date palm plantations which require irrigation with increasingly saline water (averaging 6–7 g/L in 2007) as depletion of groundwater resources require ever deeper wells. Marked by arid weather conditions with very low and erratic rainfall (72 mm yearly average), temperatures ranging from 10 °C in January with occasional freezes to 40 °C+ in summer months, high year-round evapotranspiration (≥1.86 mm/day in December ≤10+ mm/day in July and August), strong winds (≥10 m/s to ≤14 m/s) with sand storms, so freshwater availability and increasing plant cover are vital regional issues. Also of great concern was the situation of the 150 km drainage canal (for the saline water leaching from the palm plantations' irrigation), being increasingly polluted with untreated or insufficiently treated sewage and other contaminants when it used to support fish and birdlife (Fig. 20.7).

The IE was subsequently invited in 2006 to submit a tender to the Ministry of Water Resources (Department of Sanitation and Environmental Protection – Ministère des Ressources en Eau/Direction de l'Assainissement et de la Protection de l'Environnement – MRE/DAPE), with co-funding from the municipality of Tamacine and the Belgian Technical Cooperation – ADB/CTB, to develop new integrated water resources management practices. Included with the construction of the constructed wetland treatment plant was a 3-day design and maintenance workshop for engineers, officials, architects, agronomists and students, including manuals. In 2007, the design and blueprints were ready and WWG-I supervised the construction of a STP to treat the sewage of 100–150 people (15 m^3/day), including from the nearby mosque in the old historic Tamacine Ksar built in 782 A.D. Known for its unique feature of being built on layers of palm trunks, the Ksar includes a prominent 1196 A.D. minaret, 22 m high. Considered one of the most beautiful archeological sites of the Algerian Sahara, the Ksar was classified in 2013 as a national heritage [12].

At the time, as only 20 families still lived in the Ksar (but the area was to increase population under planned restoration and rehabilitation), it was agreed with local

Fig. 20.7 Photos of the area's date palm plantation drainage channel increasingly used as sewage and general pollution sink, Tamacine, Algeria (field visit 2006)

authorities that 13 m^3/day would be pumped to the STP from a nearby sewage lifting station (station de refoulement El Bohour) until full occupation occurs.

Anticipating 795 mg/L incoming BOD_5 and further downstream uptake of nitrogen and phosphorus by plant life, the STP was designed to be entirely serviced by gravity and not require mechanical pumps, with a constructed wetland (subsurface horizontal-flow) as secondary treatment and return of its treated water to a newly planted area adjacent to the CW for further nutrient uptake. In the shape of a 400 m^2 crescent moon, the CW is waterproofed via 350 kg/m^3 reinforced concrete made with sulfate-resistant cement (Ciment Résistant aux Sulfates), followed by a subsurface 3/1000 gradient gravity-fed drainage system of 468 linear meters (with no line exceeding 15 m to ensure good water distribution). For future implementations, another option (could also be cheaper) would be to use the treated water in a pond system with fish before reintroduction into agriculture, instead of through planted subsurface irrigation trenches.

The CW unit is preceded by a 2-chamber 34.7 m^3 septic tank as primary treatment (instead of 45 m^3 initially designed because of budget constraints), with a man-made natural filter at its exit prior to entering the CW as no prefabricated filter could be locally sourced. The CW unit's Control Box acts as the visual tester of the system's water flow and level, as well as the area through which all treated water gets further distributed through the drainage network (Fig. 20.8). The STP is at 33°1′5.78"N latitude and 6°1′9.20″E longitude.

The residence time of the water inside the CW is 6.28 days during lower evapotranspiration months and 7.21+ days during the hotter months of April to October. Wastewater is 0.55 m from the bottom of the completely level CW bottom and kept below 10–15 cm of screened and washed limestone ($CaCO_3$) gravel to avoid

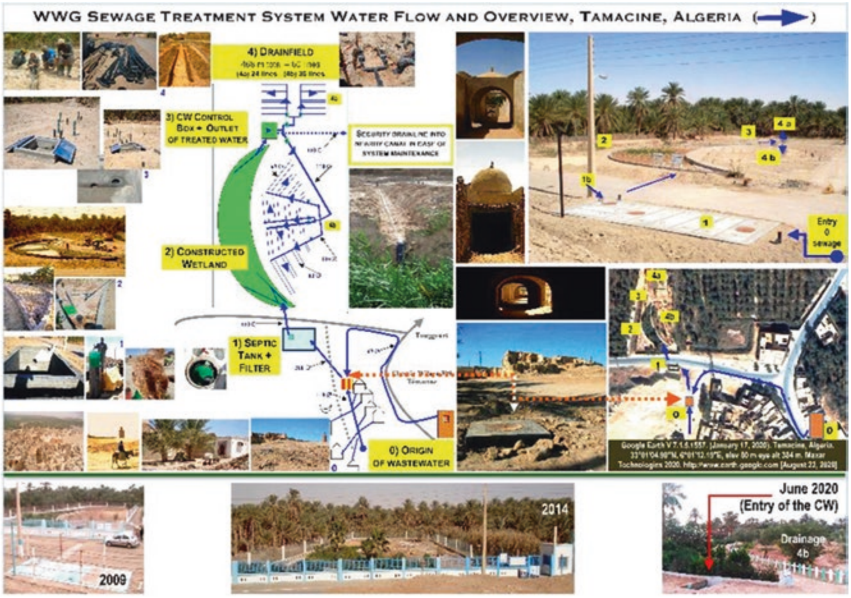


Fig. 20.8 Overview and photos of the WWG system, 2007–2020, Tamacine, Algeria

malodor and mosquito breeding. Total system volume is 260 m^3 including gravel and sewage capacity is 88 m^3.

Using the system as a showcase and testbed for the region, the design team called on the expertise of agronomist and landscape designer Maurice Levy of Earth & Water and established an informal partnership with the local Touggourt branch of INRAA, Algeria's national agronomic research center. A total of 941 plants from 23 species, including 14 test species, were planted in the constructed wetland of which at least 400 were deep-rooted.

Water quality test results have consistently reached Algerian and international standards of water purification through now more than 13 years of operation (Table 20.3), with the slight variability inherent to all treatment systems and even more so in living systems. Within 3 months of planting, the CW lost 572 of its initial 941 plants. All but one of the 407 total *Vetiver zizanoides,* which was selected for its environmental hardiness, deep-rooted growth pattern and high salt tolerance (Fig. 20.9) died. Because the plants weren't locally available locally, they were imported from a farm in Morocco with the objective of making Vetiver available in the country for future applications.

It appears that the effect of evapotranspiration on the salinity of the CW and thereby on its plant life has been much greater than initially foreseen. Due to unexpected construction delays, the septic tank was only operational after 44 days of the CW being already planted, causing us to use date palm irrigation water with its high salinity (average of 6 g/L, instead of the 2–3 g/L average in tap water expected from the septic tank – and which has since been the average incoming water salinity).

Table 20.3 Water quality results, examples from 2007 to 2020 from WWG system, old Ksar, Tamacine, Algeria compared to the local activated sludge conventional sewage treatment plant in Touggourt

SEWAGE EFFLUENT TREATMENT LEVELS WWG SYSTEM, OLD KSAR, TEMACINE, ALGERIA (2007 - 2020)													Sample results from nearby conventional treatment plant Touggourt, Algeria (Activated Sludge)		
Common Parameters - IN: INLET of the CW (Exit of the septic tank) - **OUT: OUTLET of the CW** (Control Box) - **RED %: Reduction levels**	2007 25 September			2008 June			2013 Average 4 month Aug-Sep-Oct-Nov			2020 Average 12 month Mar 2019 - Feb 2020			2008		
	IN	OUT	RED %	IN	OUT	RED %	IN	OUT	RED %	IN	OUT	RED %	IN	OUT	RED %
pII	7.33	7.48	–2.0				7.105	6.92	2.6	7.56	7.13	5.7			
Temperature (°C)	35.60	32.3	9.3				28.688	27.19	5.2						
Ce (mmho/cm)							1.65	2.15							
TSS (Total Susp. Solids) (mg/l)	837.00	49.5	94.1	501.70	22.43	95.5	383.75	21.75	94.3	342.21	16.82	95.1	803.59	21.84	97.3
COD (mg/l)	563.00	35	93.8	481.75	75.63	84.3	352.63	35.38	90.0	263.79	29.00	89.0	421.5	15.95	96.2
BOD5 (mg/l)	450.00	25	94.4	372.75	60.12	83.9	310.63	27.13	91.3	146.63	12.41	91.5	312	10.83	96.5
N-NO3 (mg/l)	35.00	20.2	42.3	35.00	29.29	16.3	35.45	7.94	77.6	28.48	4.05	85.8	35	7.90	77.4
N-NO2 (mg/l)	1.27	0.29	77.2							0.0454	0.014	68.4			
P-PT (mg/l) Total phosphorus				31.71	23.57	25.7							30.88	5.66	81.7
PO4 (mg/l)	31.00	15.5	50.0							10.55	0.26	97.6			
Total Coliforms 30 (gems/100ml)				110000	3233	97.1				4586.75	3	99.9	110000	9300	91.5
DATA Algeria: Office National d' Assainissement (ONA), Algérie, STEP de Touggourt , INRAA, 2007-2020															

The rapidly increasing evapotranspiration of this hot weather period, coupled with lack of circulating wastewater, meant that the salinity to which the still young plants were exposed may have caused their roots excessive stress. Additional adverse factors were having to plant right before the high temperatures and strong winds of the summer period and bare-rooted Vetiver planting rather than containerized or with root balls dipped in a mud slurry before transplantation (as is done in China and SE Asian countries, for example, with great success).[1]

Despite the system's maintenance training given, a lack of sufficient water inside the CW unit for over 48 h at the beginning of the STP operation could also have occurred since the agency in charge of system maintenance (Office National de l'Assainissement Algérie, ONA/DAOR) was still new to the functioning of a CW and in particular as it pertains to its plant life; or the pump needed to deliver the 13 m^3/day minimum to the primary system may have failed. If this occurred, the shoots inside the CW still too young to survive such a stress would have dried out. The STP also lost the 138 fruit trees initially planted in the drainage area due to excessive soil salinity and lack of mulching. However, the treatment plant's drainage area supports, as of 2020, 13 Olive trees (*Olea* spp.), 23 Dodonea viscosa and 90 m^2 of various grasses with sole supplemental tap water irrigation twice a week during the three hottest months, June through August (Fig. 20.10).

[1] Personal communication with Vetiver z. specialists Paul Truong, Richard Grimshaw and Criss Juliard, Nov. 2007.

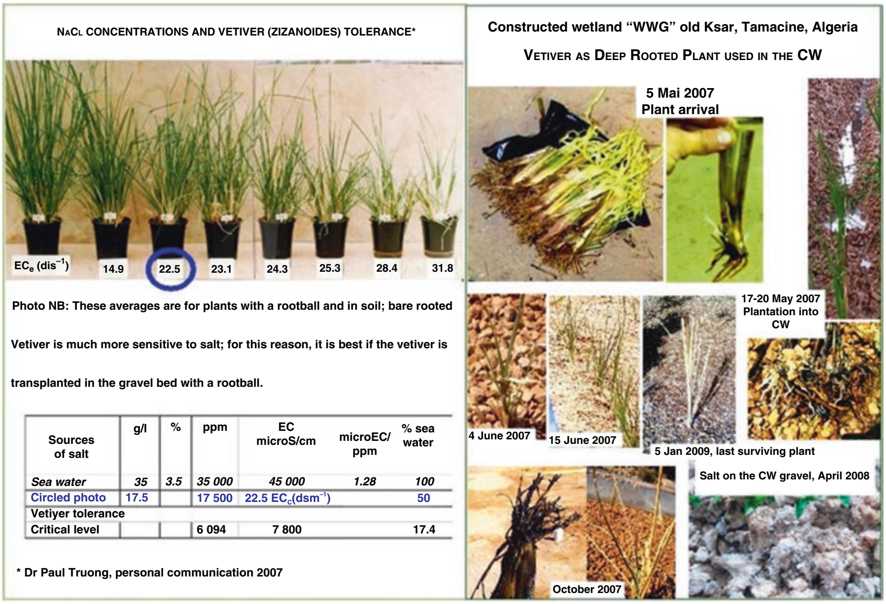


Fig. 20.9 Salinity and *Vetiver zizanoides* in the CW Temacine, Algeria, 2007–2009

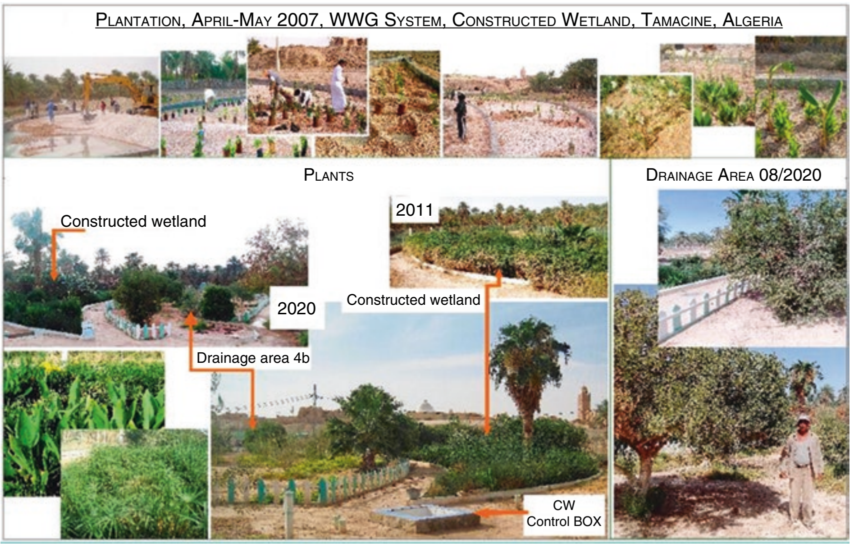


Fig. 20.10 Overview of the planted WWG system, Tamacine, Algeria, 2007–2020

To our great regret but understanding considering the local circumstances and difficulties, the *Vetiver z.* plant was replaced among others by 14 plants of *Typha latifolia* in 2008 inside the CW, which while being easily available, free and effective, is a highly invasive and aggressive plant, eventually shading and out-competing most other species. Typha also enters a dormant phase after harvest that can last several months depending on climate, unlike the Vetiver which will regrow immediately and rapidly [13]. Four pomegranate trees (*Punica granatum*) survived well at first but only *Canna indica*, Papyrus (*Cyperus* spp.), *Juncus* spp., *Nerium Oleander* and *Washingtonia filifera* appear to be thriving as of August 2020.

The WWG system keeps on achieving high levels of water purification fulfilling its priority objective of secondary treatment 13 years after its implementation and supports an important and diverse biomass vegetation. It is hoped that good maintenance will continue with a special attention to the quantity of water it was designed for (with occasional allowed variance of 10–15% more or less, but only once plants have matured enough with established root systems), and the *minimum* number of 940 plants of which 1/3 minimum should be deep-rooted. Checking on the filter at the exit of the primary treatment (here the septic tank) and maintaining a tight-fitted lid on the CW's Control Box to prevent malodor and to protect the drainage network from clogging, are also key elements to the continued long-term trouble-free operation of the STP.

The WWG system received an initial 1-year collaboration and maintenance contract from the Ministry of Water to the Ministry of Agriculture that allowed INRAA to start an agronomical study while providing maintenance services.

The treatment plant's maintenance requires about 3 h per week to check on the septic tank's filter, the constructed wetland's water levels, the pruning of plants, the removal of plant trimmings and finally on the drainage of the system [14]. As with all CW systems, the most maintenance after some years could consist of washing/flushing the gravel, purging the drainage system and replanting if necessary and the treatment plant can be expected to continue for another cycle of 20–30+ years, providing reliable, productive and resilient treatment, with minimal if any external power needs nor chemical products. It is important to mention that the success of the system's operation relies on a strict application of the design and attentive construction; the WWG team was lucky that the local construction foreman (Tahar Lambarkia) quickly grasped the principles of CW sewage treatment with its simple yet essential and fine-tuned construction parameters.

In 2020, the ten or so extra *Vetiver* z. shoots that were selected for planting in soil are thriving and have generated hundreds of offshoots at INRAA and in various farms, so there are now reliable local sources of this important bioengineering plant[2] in the region. In addition to its capacities for water purification and uptake of N and P, its 4+ meter deep sturdy root system has the capacity to act as a kind of 'vegetal nail', a type of living reinforced concrete that has been used in a diversity of countries as soft engineering on roads, pathways, waterways, as well as in long-term and cheap yet resilient anti-erosion measures [15]. The success of Vetiver's introduction in the region also opens the possibility of removing the locally

[2] For the wide range of *Vetiver zizanoides* applications, see http://www.vetiver.org/ and http://www.vetiver.org/g/archives_plant.htm

abundant Typha from the CW and reintroducing it along with other species to enhance the biodiversity and productivity of the overall system.

The Tamacine WWG/CW system led the Algerian Ministry of Water Resources to entrust us and then local partners Nationale de l'Eau et l'Environnement (NEE), to conduct another study for three further STPs in 2012 for a total population equivalent of about 10,000 with reuse of treated water in agriculture in the northern wilayas (districts) of Blida (Meftah, Zaiane, 800 m^3/day), Tipasa (Mahiddine Abed, Ain Tagourait, 150 m^3/day) and Boumerdes (Khemis el Khechna, 400 m^3/day). As of 2018, it has funded another 50+ new constructed wetlands for populations of over 10,000 in 21 districts throughout the country. Beyond its mandate of acting as an integrated wastewater treatment system, the Tamacine WWG system has also served as a great educational tool, being used as a basis of study by several researchers, institutions and universities [e.g 16–19]. Local residents and families, children and students also use the WWG system as a recreational and educational space as it is slowly being developed into a public park.

20.2.5 El Chibaish, Southern Iraq

Some of the earliest Western civilizations emerged in the marshes of Southern Iraq, a possible site of the "Garden of Eden", covering 25,000 km^2, once the third largest wetlands in the world. The marshes, formed by the Tigris and Euphrates rivers, are home to one of humanity's oldest cultures: the Marsh Arabs. The area in 2013 became Iraq's first National Park and in 2016 UNESCO designated the marshes a World Heritage Site. Southern Iraq is a high biodiversity area and a major pathway for migratory birds [20].

Local climate conditions are generally hot and dry, characterized by long summers and short winters, influenced by the subtropical aridity of the Arabian desert areas. Summer temperatures can reach 45 °C or more. Usually there is no precipitation from June to September. Even in the highest rainfall months of December and January, rainfall only averages 20 mm/month. Therefore, the water in the marshlands doesn't come from local or regional rainfall. Saddam Hussein diverted the rivers and drained the marshlands in the early 1990s after Shi'ites rebelled there against his government. This turned the historic wetlands into a desert until local residents and Nature Iraq, a leading national organization for nature and environment preservation, destroyed the diversion canals in 2003, letting water begin the process of restoring the wetlands. Hundreds of thousands of Marsh Arabs, forced to flee, began returning to southern Iraq.

Water levels in the southern Iraq marshes now depend on political relationships and water usage in the Tigris/Euphrates watersheds in Syria, Turkey, Iran and northern Iraq. Precipitation is highly variable and increasingly the rivers' water is dammed or diverted for farming and urban populations, diminishing how much reaches the marshes. These climatic and political conditions generate years of abundance and years of drought in the marshes which now cover only about half of their historic range.

After decades of wars and social unrest, the southern Iraqi marshlands face a new threat in their role as a pollution sink. Garbage, sewage discharge, unplanned urbanization and human trash are now adversely impacting this historical site as well as increasing salination of its waters due to restricted flows.

The Eden in Iraq WWG project is a cooperation between the IE and WWG-I and its local umbrella organization, Nature Iraq, whose marshland office is directed by Eng. Jassim Al Asadi. The project is in El Chibaish, the largest of the Marsh Arab cities (63,000 inhabitants) situated next to the Euphrates river on the border of the Central Marsh, between Basra and Nasiriya in Dhi Qar Province. Concept and design work began in 2013 when project director Meridel Rubenstein obtained a grant from Nanyang Technological University in Singapore to allow an international team of WWG-I and IE researchers to start assessment of the sewage problems of the area and to convene meetings and workshops with local municipalities, government representatives and technicians. Tocchetto et al. reported the steps of the project's development which received successive approval by local, provincial, national governments and environmental authorities [21, 22].

El Chibaish has two sewage network lines that collect some of the city's businesses and houses wastewater. In other parts of the city, and for those unable to afford the connection to the sewage lines, wastewater is discharged from homes directly into their adjacent environment in open ditches, highly dangerous for public health.

Since the collection and switch station system was installed in 2014, over 1000 m^3 of wastewater is discharged to the marshes each day. Around 7500 people, releasing 140–160 l/day are serviced by the system. The sewage is collected in the two pumping stations where only partial sedimentation of solids occurs before sewage is pumped into an open channel flowing into the marshes. This open canal is 900 m long and is also used by people traveling to the marshes with boats. It is foul-smelling, very unhealthy for El Chibaish residents and also causes many environmental problems for the plants and animals of the marshes (Fig. 20.11).

The Eden in Iraq WWG project will install adequate primary treatment in the collecting stations, and create a series of constructed wetlands for secondary treatment with a final greened area.

Project design celebrates traditional Marsh Arab culture by incorporating adobe bricks, woven reed, and ceramic tiles and using valued plants, including some mentioned in the Koran and Bible. The WWG design is inspired by the traditional Marsh Arab wedding blankets (Fig. 20.12).

The planned system includes a surface flow bed of 700 m^2 and horizontal flow subsurface CWs totaling 12,000 m^2. The treated wastewater from the WWG will be used for subsurface irrigation of other attractive and useful shrubs and trees, enlarging the green zone created by using more of the water and nutrients.

The project is to cover a total of 26,500 m^2 including the garden and cultural structures to make the area an attractive, shady green park for El Chibaish residents

Fig. 20.11 The El Chibaish, Iraq water channel where raw sewage pumped from the switch station flows into the marshes

and travelers. The green and flowering site will be complemented with art and tributes to the area's history and culture.

Southern Iraqi conditions obliged the WWG designers to take into consideration the high value of shade structures and ways to prevent plant damage from sandstorms and extreme heat. The artistic structures are not only aesthetic and cultural but have technical benefits. For example, the adobe walls surrounding the WWG will prevent sandstorm damage and exclude water buffalo, which wander freely during the day, from damaging the public garden (Fig. 20.13).

The Eden in Iraq WWG project is still in its planning and fund-raising phase though it has received local and national governmental approval and generated enthusiasm as a model for dealing with wastewater problems throughout Iraq. In 2019, it received formal approval by the Iraqi Ministry of Water Resources and the Iraqi government committed to funding the initial stages of the project. It has also received recognition as a UNESCO Green Citizens 2020 endeavor. However, recurrent political instability, warfare and tribal conflicts may delay project implementation.

20.3 Conclusions: Constructed Wetlands as Nature-Based Solutions for Wastewater Treatment and Intelligent and Resilient Resource Utilization for Environmental Integration

In our combined 30 years' experience of using CWs as wastewater treatment systems and in the examples presented above, it has become evident how reliable and resilient these created ecosystems are. Their deceptively simple designs and

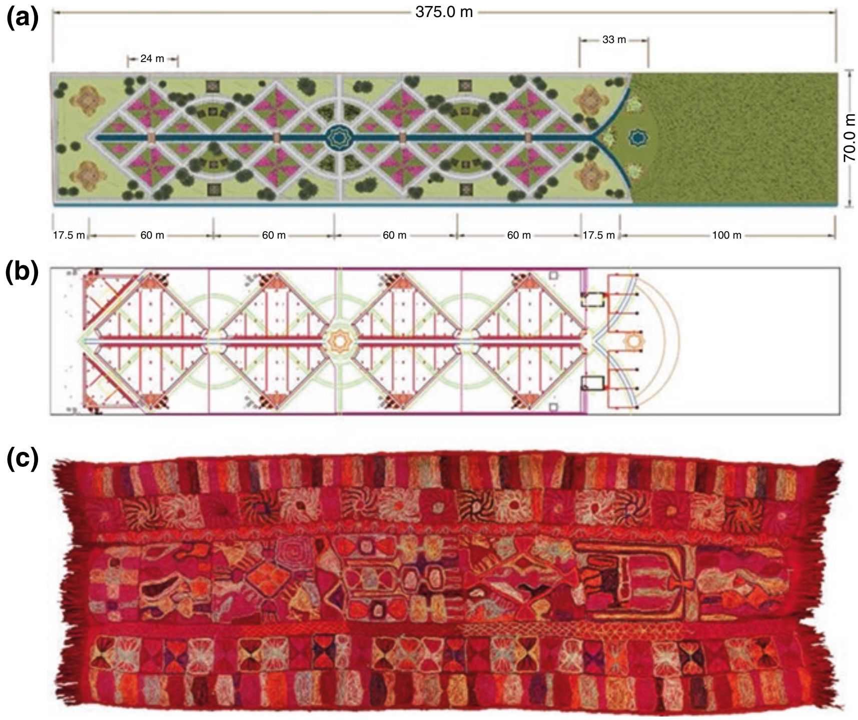


Fig. 20.12 Scheme of the WWG system in Iraq showing the layers of the work; (**a**) the overall garden (**b**), the WWG treatment beds (c), the traditional Marsh Arab wedding blanket which inspired the design

Fig. 20.13 Artist's visualization of a portion of the Eden in Iraq WWG parklike environment (drawing by Bernard Du for the Eden in Iraq WWG project, https://www.meridelrubenstein.com/wastewater-gardens/)

maintenance hide highly complex and efficient biochemical processes that reach the purification standards of very costly and non-sustainable high external-energy-dependent systems that seek to eliminate what is a precious resource in overall ecosystem and climate health. For CW designers, sewage with its water and" pollution" is appreciated as a resource to use and recycle as completely as possible. This is a profound paradigm shift in the fields of wastewater treatment and sanitation policies.

Vymazal also reported successful treatment wetlands in hot climates like in Africa, Asia, Central and South America [23]. Stefanakis reported the recent efficient use of wetlands technology in industrial wastewater in Oman [24, 25] and Tocchetto described encouraging applications in the Caribbean area [26]. Further research needs include quantifying some of the collateral benefits of CWs such as biomass creation, carbon sink capacities as climate equilibrium contributors, oxygen production and biodiversity and habitat enrichment.

CW test analyses consistently meet or exceed international legislative requirements. When they do not because the local situation has changed (e.g. in the case of increased input of wastewater to be treated or if the treated water must be used in a more sensitive ecological zone) the constructed wetland can be enlarged and/or reengineered with increased primary treatment to achieve the strictest water quality standards. If the influent wastewater is saline, then appropriately salt-tolerant halophytic plant species such as mangroves or saltmarsh plants should be used. For applications with limited space available, CW systems can be designed to create buffer zones and fully integrate urban needs such as sidewalks, delineation of areas including parking spaces, municipal parks, etc. The flexibility inherent in constructed wetland based systems is just beginning to be explored.

One of the challenges in implementation and maintenance at a large scale is ensuring interdisciplinary collaboration combining the knowledge and practice of hydrology-trained technicians and scientists in ministries of water, sanitation and public health with those provided by gardeners and agronomists in ministries of agriculture and the environment. Applying CW systems when possible in hot and arid climates should be a high priority for all public, governmental and funding agencies looking for less expensive and longer-lasting solutions for treating wastewater while conserving water and creating green areas.

References

1. Nelson M, Burgess T, Alling A et al (1993) Using a closed ecological system to study Earth's biosphere: initial results from biosphere 2. BioScience 43(4):225–236
2. Nelson M, Allen J, Alling A et al (2003) Earth applications of closed ecological systems: relevance to the development of sustainability in our global biosphere. Adv Sp Res 31(7):1649–1656. https://doi.org/10.1016/S2073-1177(03)00104-2
3. Nelson M (2018) Pushing our limits: insights from biosphere 2. University of Arizona Press, Tucson

4. Alling A, Nelson M, Silverstone S (2020) Life under glass: crucial lessons in planetary stewardship from two years in biosphere 2. Synergetic Press, Santa Fe, NM
5. Nelson M, Finn M, Wilson C et al (1999) Bioregenerative recycle of wastewater in biosphere 2 using a created wetland: two-year results. Ecol Eng 13:189–197
6. Nelson M, Wolverton BC (2011) Plants + soil/wetland microbes and food crop systems that also clean air and water. Adv Sp Res 47(4):582–590
7. Nelson M, Dempster WF, Allen JP (2009) The water cycle in closed ecological systems: perspectives from the biosphere 2 and laboratory biosphere systems. Adv Sp Res 44:1404–1412
8. Nelson M (2014) The wastewater gardener: preserving the planet one flush at a time. Synergetic Press, Santa Fe, NM
9. Nelson M (1998) Limestone mesocosm for recycling saline wastewater in coastal Yucatan, Mexico, PhD dissertation, Department of Environmental Engineering Sciences, University of Florida, Gainesville, p 329
10. Nelson M, Tredwell R, Czech A, Depuy, G, Suraja M, Cattin F (2008) Worldwide applications of wastewater gardens and Ecoscaping: decentralised systems which transform sewage from problem to productive, sustainable resource. In: Mathew K, Dallas S, Ho G (eds) Decentralised water and wastewater systems: international conference, Fremantle, Western Australia, 10–12 July 2006, IWA Publications, London, pp 63–73
11. Nelson M, Cattin F, Hafouda L, Rajendran M (2008) Value-adding through creation of high diversity gardens and ecoscapes in subsurface flow constructed wetlands: case studies in Algeria and Australia of wastewater gardens systems. In: IIth international conference on wetland systems for water pollution control, Indore, India, International Water Association (IWA), Vikram University IEMPS, ICWST, November 2008
12. Merah A et al (2019) Processus de valorisation du Ksar de Temacine, quels dispositifs et stratégie de communication? In: 2019 ICOMOS Advisory Committee Scientific Symposium, Marrakesh, Morocco. https://scholarworks.umass.edu/icomos_isccl/2019/papers/33/
13. Truong PN, Hart B (2001) Vetiver system for wastewater treatment. Office of the Royal Development Projects Board, Bangkok, p 26
14. Khemici Y (2014) Etude de la qualité physico-chimique et bactériologique d'une eau usée épurée par un lit de plantes; thesis, Master in Technical Science, Hydraulics, with a specialty in Wastewater Treatment, University Kasdi Merbah Ouargla, Algeria
15. National Research Council (1993) Vetiver grass: a thin green line against erosion. National Academies Press, Washington, DC. https://doi.org/10.17226/2077
16. Bachi OE, Halilat MT, Bissati S (2015) Sewage in Algerian oasis: comparison of the purifying efficiency of two processes (WWTP and WWTAS). Energy Procedia 74:752–759
17. Hafouda L, Hadad M, Arif Y, Djafri K, Balleche O, Talab B, Ebba MS, Nelson M, Cattin F, (2008) L'épuration des eaux usées domestiques par les plantes; une alternative à encourager pour une préservation durable de l'environnement en zones arides: cas de la station pilote du vieux Ksar de Témacine, Touggourt, Algérie. In: International symposium on dryland cultivation, optimization of agricultural production and sustainable development, Centre for Scientific and Technical Research on Arid Regions (CRSTRA), Biskra, 13 and 14 December 2008
18. Hammadi B, Bebba AA, Hacini Z, Zeghdi S (2013) Gardens planted with Macrophytes filters, purification performance in an arid climate – pilot station of Témacine, Ouargla (Algeria). Int Lett Chem Phys Astron 13:259–268
19. Tidjani H (2019) Etude de l'Efficacité et la Valeur Ajoutée d'un Système de Phytoepuration Pilote en Algérie: La Station Pilote Vieux Ksar Temacine; thesis, master in agronomical sciences with a specialty in vegetation production, University El Oued, Algeria
20. Salim M, Rahim M, Bachmann A, Ararat K, Raza H (2018) Key biodiversity areas in Iraq. Ministry of Environment and Nature Iraq Publication, 297 p
21. Tocchetto D, Rubenstein M, Nelson M, Sathikh P, Cattin F (2013) Marshes of Southern Iraq: New Eden in Iraq treatment wetlands project. In: Proceeding of international conference 1–4 September 2013, Society of Wetland Scientists European Chapter, Padova, Italy

22. Tocchetto D, Rubenstein M, Nelson M, Al Asadi J (2021) Circular economy in the Mesopotamian marshes: the Eden in Iraq wastewater garden project. In: Stefanakis AI, Nikolaou I (eds) Circular economy and sustainability: environmental engineering, policy, and management, vol II. Elsevier, Amsterdam
23. Vymazal J, Kröpfelová L (2008) Wastewater treatment in constructed wetlands with horizontal sub-surface flow. Springer, Dordrecht
24. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, pp 25–42
25. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12(6):1665. https://doi.org/10.3390/w12061665
26. Tocchetto D (2007) Treatment of wastewater with natural systems and reuse of clean water for different applications in the Caribbean Islands. In: Proceedings of CWWA2007 conference 1–5 Oct 2007, Caribbean Wastewater Association conference 2007, St. Kitts, West Indies

Chapter 21
Selected Constructed Wetlands Case Studies in Africa, Asian and Latin American Countries

M. A. El-Khateeb and H. I. Abdel-Shafy

Abstract Low-income areas can rarely afford centralized wastewater treatment facilities, let alone possess the technical knowledge required to administer them. As a result, alternative treatment approaches are necessary, especially in developing countries, that should combine acceptable performance, cost-efficiency, and, sustainability aspects. The constructed wetland (CW) system is a simple technique that can be applied in villages and rural areas that are not served by sanitation systems and sewer networks. This technology is inexpensive (especially if the land is available) and does not require skilled workers to manage it. There are two main types of CWs (according to the direction of water flow); horizontal and vertical flow CWs. Horizontal flow systems are classified into free water surface (FWS) and subsurface flow (SSF) CWs. CWs are designed as tanks with different dimensions that are filled with media such as sand and planted with swamp plants. These systems are typically used as a secondary treatment step due to the hydraulic flow and potential clogging of the media. There are several primary treatment systems that are coupled with CWs technology. The upflow anaerobic sludge blanket (UASB) is a popular system that can be integrated with CWs, as well as the conventional sedimentation tank and the septic tank. These techniques could be used in villages, resorts, and camps. The hydraulic residence time in these systems ranges from hours to days, depending on the type of constructed wetland used. The characteristics of this green technology make CWs an attractive solution for low-income countries in Africa, Asia, and Latin America.

Keywords Constructed wetlands · Case studies · Hot and arid climate · Wastewater treatment · Asia · Africa · Latin America

M. A. El-Khateeb (✉) · H. I. Abdel-Shafy
Water Research & Polluted Control Department, National Research Centre, Dokki, Cairo, Egypt

A. Stefanakis (ed.), *Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates*, Wetlands: Ecology, Conservation and Management 7,
https://doi.org/10.1007/978-3-031-03600-2_21

21.1 Introduction

Tropical countries are located approximately in the center of the globe between the Tropic of Cancer latitude lines and the Capricorn Tropics. The equator and part of North America, South America, Africa, Asia, and Australia are tropical regions. They account for 36% of the Earth's area and are occupied by about a third of the inhabitants of the planet. Natural and constructed wetlands (CWs) are wetland systems classifications. Natural wetlands are wet areas during any time of the year due to their location in the landscape. Wetlands are called swamps, marshes, bogs, fen, or sloughs, depending on existing plants and water conditions and on the geographic setting. Natural wetlands have probably been used for wastewater disposal for as long as wastewater has been collected, with documented discharges dating back to 1912 [1].

The main issues for most developing countries are human health risks due to sewage pollution and shortage of water resources, thus making the wastewater treatment and reuse of treated wastewater of the highest priority [2]. Sustainable water management combined with wastewater treatment and water recycling, wherever possible, is the only way to meet the challenge of water shortage in arid and semi-arid countries [3]. In addition, the increasing scarcity of water in the world combined with the rapid population increase in urban areas is giving cause for concern and the need for appropriate water management practices [4].

Natural wetlands were used for wastewater treatment for a long time without realizing their specific role. The efficiency of treatment by several wetland plants (e.g., *phragmites australis*) was reported in the 1960s [5]. Worldwide, attention has been paid to investigating the removal of different pollutants such as trace elements and other toxic substances by natural wetlands [6]. Absorption of nutrients for plants growth when the nutrient availability is high occurs in many plant that can concentrate sediment and/or water nutrients by a factor of several thousand [6].

Wastewater reclamation with constructed wetland (CWs) has become widely applied worldwide over the last few decades. CWs provide a low-cost, simple, and on-site alternative technology [7–9]. These systems use natural processes using shallow beds or channels (with less than 1 m depth), helophytes, substrates (soil, sand, and gravel), and a variety of micro-organisms to improve the quality of the wastewater [9–11]. CWs are capable to reduce contaminants including toxic compounds, metals, pathogens, inorganic, and organic matter from different liquid wastes [12–15]. Various treatment mechanisms, including chemical precipitation, sedimentation, filtration, adsorption, microbial interactions, and helophyte absorption [11, 16] are used to reduce or eliminate pollutants. All these processes take place simultaneously. Influent nutrients support helophyte growth, which transforms inorganic chemicals into organic matter and forms the basis of the CW food chain [17]. Microorganisms are involved in the oxidative removal of pollutants [18] and have been reported for their ability to remove toxic organic compounds added to wetlands [19–22]. CWs have low construction and maintenance costs and a higher aesthetic look [9, 23].

21.1.1 Constructed Wetland Designs

CWs are subdivided into two groups depending on the wastewater flow:

(i) Surface flow (SF) or free water surface (FWS) wetlands (Fig. 21.1a), in which wastewater flows horizontally through the substrate. These CWs look like natural wetlands in appearance and function, with open water areas, emergent plants, different water depths, and other wetland characteristics. A typical FWS consists of several components that can be modified between different applications but retain essentially the same features. Berms that enclose the treatment cells and inlet structures to manage and distribute influent wastewater evenly for best treatment are among these components. Various combinations of open water areas and fully vegetated surface areas in relatively shallow beds or channels, and outlet structures complement the even distribution provided by inlet structures and allow adjustment of water levels within the treatment cell. Often site characteristics, rather than predetermined design goals, determine the shape, size, and complexity of the design [10, 11].

(ii) Sub-surface flow (SSF), in which the wastewater flows below the substrate surface. They are also called vegetated submerged beds (VSB), consisting of permeable media-rock, gravel, or coarse sand to support the root system of the emergent vegetation. The bed's depth varies from 0.45 to 1.0 m, with a slope of 0–0.5%. SSF CWs also contain berms, inlet, and outlet structures for regulation and distribution of wastewater flow [10, 11].

A wide range of submerged and floating plants are used in CWs. The common reed (*Phragmites australis*), cattail (*Typha* spps.), bulrush (*schoenoplectus*), and *canna indica* are common species (Table 21.1) widely used in SSF CWs. The treatment efficiency of these systems depends primarily on wetland design, hydraulic residence time (HRT), hydraulic loading rate (HLR) and pollutant types, microbial interactions, and climate factors.

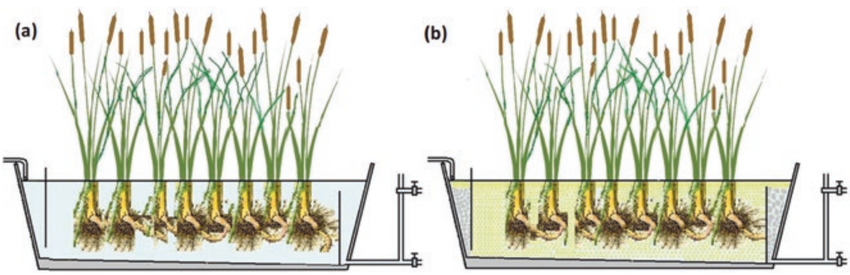


Fig. 21.1 Schematic layout of (**a**) Free water surface wetland (FWS) and (**b**) subsurface flow surface wetland (SSF) CWs

Table 21.1 Common plant species used in CWs for wastewater treatment

Floating	Submerged	Emergent
Lagarosiphon major	*Eggeriadensa* (Brazilian waterweed)	*Scirpus robustus*
Salvinia rotundifolia	*Ceratophyllum* spp. (Coontails)	*Scirpus lacustris*
Spirodela polyrhiza	*Elodea* spp. (waterweeds)	*Schoenoplectus lacustris*
Pistia stratiotes (water lettuce)	*Myriophyllum* spp. (watermilfoils)	*Phragmites australis*
Lemna gibba (duckweeds)	*Cacomba caroliniana* (fanwort)	*Phalaris arundinacea*
Lemna minor (duckweeds)	*Najas* spp. (water nymphs, naiads)	*Typha domingensis*
Eichhornia crassipes (water hyacinth)	*Potamogeton* spp. (pondweeds)	*Typha latifolia*
Wolffia arrhiza	*Utricularia* spp. (bladderworts)	*Canna flaccida*
Azolla caroliniana	*Isoëtes* spp. (quillworts)	*Iris pseudacorus*
Hydrocotyleum bellata	*Hydrilla verticillate* (Hydrilla)	*Scirpu svalidus*

21.2 Case Studies of CWs in Africa

An overview of selected CW case studies in African countries is presented in Table 21.2.

21.2.1 Egypt

A pilot HF CW (called Gravel Bed Hydroponic) in Abu Atwa, Ismailia, Egypt was the first model for CWs systems [24]. This HF system consisted of six inclined channels (50–100 m long, 2 m wide, and 0.3 m deep with a variable slope between 1:20 at the beginning of the bed to 1:100 at the end of the bed). The beds were filled with gravel and planted with *Phragmites australis*.

The combination of upflow anaerobic sludge blanket (UASB) followed by either FWS or SSF CWs for domestic wastewater treatment was tested by El-Khateeb and El-Gohary [8]. The design parameters such as porosity of sand and selection of appropriate plants were adjusted according to the previous USEPA [10]. *Typha latifolia* was used within the CW units. The control unit (without plants) for the SSF CW was used to investigate the role of plants during the treatment. The maximum influent OLR for the CWs was 46.8 kg BOD_5/ha/day. The SSF CW was found to be more efficiently removed COD and TSS than FWS CW. The FC reduction reached 4 log units. Also, the SSF CW demonstrated higher performance than the control unit [8]. The same pattern of using UASB and SSF CW was studied by El-Khateeb and El-Bahrawy [7]. The combined system efficiently removed COD, BOD, and TSS from 612, 419, and 235 mg/L to 57, 21, and 5 mg/l with removal percentages of 91%, 95%, and 98%, respectively [7].

Table 21.2 Selected case studies of CWs with different types in various African countries

Pre-treatment	CW type	Plant species	Efficiency	References
Waste stabilization ponds	SSF	*Phragmites australis*	66% COD, 91% fecal conforms	[26]
Septic tank	FWS and SSF	*Cyperus papyrus* and *Phragmites mauritianus*	70% COD and 80% BOD	[27]
		*Typha sp., Papyrus*sp and *Phragramites sp.*	99.6% COD	[28]
UASB	FWS or SSF	*Typha latifolia*	89% COD in SSF and 68% in FWS	[8]
UASB	SSF	*Typha latifolia*	66% COD and 70% BOD in greywater, 84% COD and 86% BOD in Blackwater	[29]
UASB	FWS followed by SSF	*Typha latifolia*	85% COD and 90% BOD	[30]
UASB	SSF	*Typha latifolia*	71% COD and 83% BOD	[7]
UASB	FWS	*Typha latifolia*	64% COD and 81% BOD	[31]
Sedimentation tank	FWS or SSF	*Typha latifolia*	FWS: 59% COD and 64% BOD SSF: 57% COD and 62% BOD	[32]
Filtration	FWS or SSF	*Typha latifolia*	FWS: 60% COD and 72% BOD SSF: 60% COD and 72% BOD	[33]
	SSF	*Cyperus papyrus* and *Miscanthidiumviolaceum*	68.6% BOD	[34]
	SSF and FWS	*Phragmites australis* and *Salvinia natans*	95% COD, 97% BOD	[35]

The UASB was used as a primary treatment step for separated domestic (grey and blackwater) wastewater in a study carried out by Abdel-Shafy et al. [29]. The HRT of the UASB was 6 and 24 h for the grey and blackwater, respectively, while the OLRs for CWs were 1.9 and 1.2 kg/m^3/day for the treatment of blackwater and greywater, respectively. The UASB effluent was improved by using SSF CWs. The removal of COD, BOD, and TSS exceeded 88%, 89.5%, and 94% for greywater, and 94%, 95.6%, and 94.9% for blackwater [29].

The use of UASB and CW was extended for studying the removal of some physico-chemical, bacteriological and parasitological parameters. The CW used was FWS and SSF in series. This study was the first hybrid CW that was tested in Africa. Significant removal of physico-chemical parameters (COD, BOD, TSS, TKN, and TP) and microbiological parameters such as fecal streptococci, *P. aeruginosa*, *Listeria monocytogenes*, total Staphylococci, Salmonellae, total and fecal coliform were found. The authors concluded that the integration of UASB and CW was a feasible wastewater treatment option [30].

Moreover, the application of CWs for the treatment of drain water was carried out in Egypt. The treatment pattern consisted of FWS followed by floating aquatic plant (FAP) CWs. *Typha latofolia* and w*ater hyacinths* were used. The levels of COD, BOD, TSS, ammonia, and phosphorus were reduced from 115, 71, 79, 5, and 1.4 mg/L to 42, 14, 14, 1.8, and 0.5 mg/L, respectively. The final effluent was complying with the National regulatory standards for treated effluent reuse [31].

In an attempt to study to enhance the performance of CWs, different inlet shapes were studied [32, 33]. Four pilots FWS and SSF CW (two for each type) were operated in parallel mode. The entrance shape was triangular and rectangular for FWS and SSF units. The HRT was 2 days in each unit. The triangular inlet shape improved the performance of the CWs as indicated by the performance of the units. The levels of COD and BOD were reduced by 12% and 36% for FWS and 9% and 21% for SSF with triangular inlet shapes than the rectangular inlet shape CWs.

21.2.2 South Africa

There were approximately 70 CWs in South Africa already in the year 1999, mostly constructed for on-site domestic wastewater treatment. CWs were also applied at different mining and industrial sites, as well as for stormwater and urban catchment management, riverine rehabilitation and protection, groundwater recharge, and development of urban nature reserves and ecological sites. The CWs were designed based on European systems. In many cases, this approach has resulted in systems failing to meet design objectives which were seen as limiting the application of that technology.

A past project identified a number of established CWs treating domestic wastewaters. The results confirmed that there were flaws in the design and operation of CWs due to a limited understanding of the mechanisms and processes of wastewater treatment through CWs. The primary performance limitation is flow control through the system. The low permeability of the bed media tends to encourage surface flow rather than filtration through the bed for systems designed with the subsurface flow, and similarly, surface flow systems demonstrate significant short-circuiting. These factors reduce the residence times and contact time opportunities for optimal treatment.

The South African CWs did demonstrate significant potential for wastewater treatment. FWS systems receiving secondary sewage can achieve removals of COD and TSS up to 20 g/m^2/day, NH_3 and NO_3 removal up to 1.5 and 6.0 g/m^2/day, respectively, but limited pathogen removal of 99%, and low phosphate removal. The SSF CWs performance was limited by the permeability, but where flow is maintainable for secondary wastewaters, COD, TSS, NO_3, and PO_4 removals were more than 85%, and pathogen removal of 10^5-fold, but NH_3 removal was below 30% due to poor oxygen transfer to the root zone. SSF gravel beds can achieve high COD removal rates at loadings up to 100 g COD/m^2/day with settled sewage, acting as anaerobic filters.

Secondary units are then required to polish residual organics, nutrients, and pathogens. The design parameters such as HRT, organic loading rate (OLR), and conductivity of the substrate were well considered for the upcoming CWs in Africa [25].

21.2.3 Tanzania

Due to the lack of resources for wastewater treatment, conventional treatment systems have not been used in Tanzania considering also their high investment and maintenance cost. On the other hand, cost-effective wastewater treatment methods are widely applied. CWs are a method that can compete with conventional treatment systems at a lower cost. Until the year 2000, no wetlands have been used for treating wastewater in Tanzania. Therefore, a first attempt was made to promote the use of SSF CW coupled with waste stabilization ponds (WSP) for wastewater at the University of Dar es Salaam (Fig. 21.2). The field tests were conducted at low and high filtration rates of 0.27 m/h and 2.3 m/h, respectively for a period of 4 weeks. Treatment effectiveness was evaluated which indicated high removal efficiencies, 80% for SS. 66% for COD, 91% for fecal conforms (FC) and 90% for total coliforms (TC) achieved at the low filtration rate. Thus, CWs if properly designed, operated, and maintained can provide an efficient and economical means of upgrading the quality of secondary treated wastewater to an acceptable level [26].

21.2.4 Uganda

A pilot HF CW receiving anaerobic lagoon effluent from the Jinja Kirinya Sewage Treatment Plant was tested by Okurut [27]. The total surface area of the CW was 320 m^2. This area was divided into eight separate units. *Cyperus papyrus* was

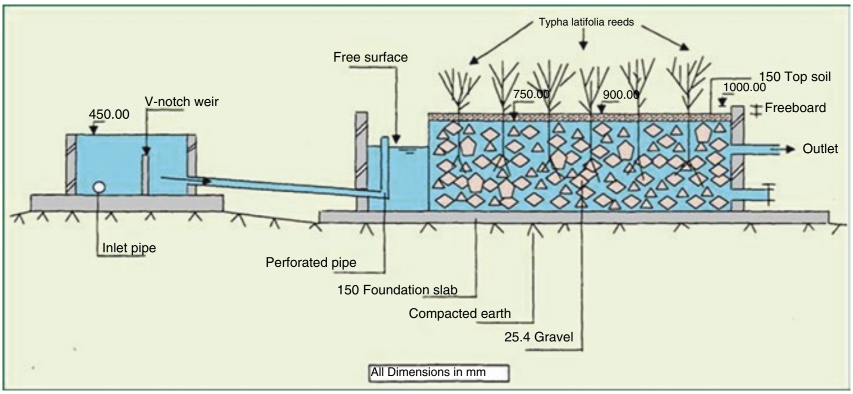


Fig. 21.2 Side view of the CW at Dar es Salaam, Tanzania [26]

planted in four FWS units were FWS and *Phragmites mauritianus* was planted in two SSF units. The CWs were operated over three consecutive phases. In the first phase, all planted units remained intact but in the second phase, plant biomass was removed from a quarter of the area of the two *Cyperus papyrus* and one *Phragmites mauritianus* CWs. In the last phase, two CWs of each plant type and one control (open) were connected in series; two other papyrus-planted CWs and unplanted sections were connected in series. The applied HLR to the different CWs ranged from 1.3 to 12 cm/day during the study period.

Removal efficiencies in both CWs' reached 70% of the influent COD and BOD at high plant densities. It increased to over 80% in the last phase. The elimination of fecal coliform in the planted CWs was associated with the reduction of both TSS and particulate organic matter. The results revealed higher removal rates for BOD, ammonium, and phosphorus in the papyrus bed CWs compared to *Miscanthidium* and the unplanted beds. Higher biomass production by the *Cyperus papyrus* was also found compared to *miscanthidium violaceum* plants which probably affected the nutrient uptake [34].

Overall, the quality of the effluent of CWs was complying with the Uganda wastewater discharge standards. The cost for CWs was nearly eight times lower than that for the conventional treatment plants.

21.2.5 Kenya

A CW study was also carried out in Nairobi city, Kenya. Nzengy'a and Wishitemi [28] studied the treatment of domestic sewage from two restaurants, while the treated effluent was reused for various purposes. The impact of seasonal variations on the system performance was studied in wet and dry seasons. The physico-chemical characteristics of the influent wastewater and the effluent were measured; the levels of BOD_5, COD, and TSS were reduced from 1603 to 15.1, 3749.8 to 95.6, and 195.4 to 4.7 mg/L, respectively. The level of ammonia decreased from 14.6 to undetectable limits. The quality of the effluent was consistent and safe for reuse at the restaurants during the study [28].

21.2.6 Algeria

In Algeria, emergent (*Phragmites australis*) and floating macrophytes (*Salvinia natans*) in separate or mixed cultures were used for domestic wastewater treatment. The mixed plant culture recorded the highest and most significant removal potential by 97% of BOD, 95% of COD, 93% of TKN, 88% of NH_4-N, 53% of NO_2-N, and 40% of PO_4-P. The mixed culture of emergent and floating macrophytes was a simple and cost-effective method for the efficient removal of pollutants from domestic wastewater [35].

Table 21.3 Selected case studies of CWs with different types in various Asian countries

Pre-treatment	CW type	Plant	Efficiency	References
Septic tank	SSF	*Cyperus alternifolius*	72% COD	[38]
Anaerobic bioreactor	SSF	*Arundo donax*	80% COD and 82% BOD	[39]
Secondary treated wastewater treatment effluent	Horizontal vertical hybrid (HVH) followed by vertical flow (VF) SSF CWs	*Phragmites australis*, *Typha latifolia*, *Arundo donax*	80% COD and 85% BOD	[40]
	H-SSF	*Louis latifolia* and *Phragmites australis*	94% phosphate and 84% fecal coliform	[41]

21.3 Case Studies of CWs in Asia

An overview of selected CW case studies in Asian countries is presented in Table 21.3.

21.3.1 Thailand

Although many CWs exist in Thailand, no studies have been conducted on their sustainability. To overcome this problem, the sustainability of three promising CWs in very different conditions was evaluated. These were located in Koh Phi Phi, a world-famous tourist resort and holiday resort; Sakon Nakhon, the capital of the Northeast Province; and Ban PruTeaw, a little post-tsunami village on the Andaman shore. Key stakeholder interviews, questionnaires, and home interview surveys, along with current data and on-site measurements of major wastewater pollutant content were used to assess the systems and the results showed the emergence of significant management and remediation problems in the two CWs in Koh Phi Phi and Ban PruTeaw due to lack of development and maintenance after construction. The results revealed the importance of the social and cultural dimensions of sustainability. Public awareness, awareness, knowledge, local experience, and clear roles for organizations can explain the differences in the sustainability of CWs [36].

21.3.2 Nepal

In Kathmandu Valley, environmental degradation was observed due to the lack of legislation to control the discharge of untreated wastewater. Although five centralized wastewater treatment plants were located in the valley, most were out of control. In the country, CWs have gained attention for the treatment of domestic wastewater. In 1997, the first CW of Nepal was launched for the treatment of Dhulikhel hospital wastewater. Since that time, the number of CWs was increasing in Nepal to reach 13 units in 2012 for the treatment of domestic wastewater including grey water and fecal sludge. Relatively high removal efficiencies of TSS (>95%), organic pollutants, and ammonium were found in all the operating CWs [37].

21.3.3 Iran

The use of CWs planted with *Cyperus alternifolius* was evaluated for the treatment of septic tank effluent in Yazd city, Iran. Two identical CWs with an actual volume of 60 L and a 0.1 m sand layer at the bottom were used. The first CW was an unplanted unit (control) and the second had 100 *Cyperus alternifolius* shrubs of 0.04 m in height. Yazd's septic-tank treated effluent was used to feed the CWs. The HRT of the septic tank was 4 days. The results showed that COD, NO_3–N, NH_4–N, and PO_4^{-3}–P in the control and planted CW units were reduced by 72%, 88%, 32%, & 0.8% and 83%, 81%, 47%, & 10%, respectively. It was found that the remaining phosphorus can be released with the final treated effluent when the soil is saturated or influent phosphorus is decreased [38].

One of the first hybrid CW appeared in 2016 in Iran. The secondary treated effluent of the North Wastewater Treatment Plant in Isfahan was tertiary treated using four pilot-scale horizontal vertical hybrids (HVH) CWs (Fig. 21.3). Each HVH-CW unit consisted of a 100 m² horizontal flow (HF) and a 32 m² vertical flow (VF) SSF CW operating in series. *Phragmites australis*, *Typha latifolia*, and *Arundo donax*

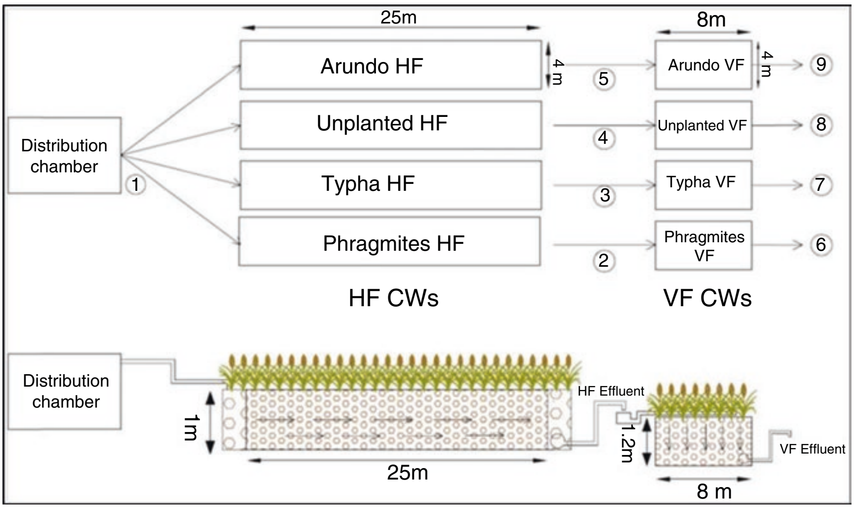


Fig. 21.3 Schematic layout plan (up) and cross-section (below) of pilot-scale hybrid CW in Isfahan, Iran and the sampling points [40]

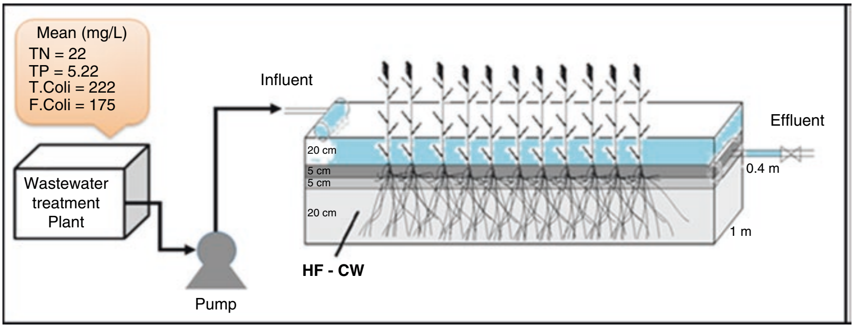


Fig. 21.4 Layout of the CW system in in the North of Iran [41]

were used in three CW units. The remaining unit was unplanned and used as a control. The substrate material was fine grain from 3 to 7 mm. The average OLR and HLR of the system were 15 g BOD/m^3/day and 5.3 cm/day, respectively. The results showed that the HVF CWs were highly efficient in removing the BOD (85%), COD (80%), TSS (79%), NH_4-N (78%), TP (74%), and fecal coliforms (99%). Only the removal efficiencies of nutrients in planted CWs were higher than those of the control unit. The effluent quality met the requirements for reuse in various applications, but bacterial contents were equal to levels that permit the reuse of effluent in the non-food crop. On the contrary, the effluent of a single HFCW was not complying with the regulatory standards for reuse [40].

Two more small-scale CWs planted *Louis latifolia* and *P. australis* were used for the treatment of domestic wastewater in Iran (Fig. 21.4). Each CW unit was planted with a single type of plant. The influent wastewater and the effluent from each CW were sampled daily for 4 months. It was found that phosphate, nitrate, fecal and total coliforms were reduced by 94%, 84%, 96%, and 94% for *P. australis* and 64%, 73%, 94%, and 92% for *L. latifolia*, respectively. In all cases, the effluent of HF-CW planted with *L. latifolia* and *P.* australis, fulfilled the wastewater discharge criteria [41].

21.3.4 Pakistan

Arundo donax plant was used in a laboratory scale CW for the treatment of anaerobic bioreactor (ABR) effluent treating industrial wastewater. Several dilutions of industrial wastewater were used to adapt the combined ABR/CW system. The ABR showed removal rates by 80%, 82%, 92%, 100%, and 92% for COD, BOD, TSS, ammonia, and nitrates, respectively. The metals removal order was Cd (3%) > Ni (79%) > Pb (85%). COD and various heavy metals were Effectively removed by the CW. The CW lowered the metal amounts of Ni, Pb, and Cd to 2 mg/L, 0 mg/L, and 0.004 mg/L, respectively. The levels of heavy metals were within the permissible water quality standards for industrial effluents [39].

Table 21.4 Selected case studies of CWs with different types in various Latin America countries

Pre-treatment	CW Type	Plant	Efficiency	References
No	SSF	*Typha latifolia* or *Scirpus*sp.	59% COD	[43]
	SSF	*Typha domingensis*		[44]
Lagoon system	SSF	*Phragmites Australis* and *Cyperus Papyrus*	81% BOD and 70% COD	[45]

21.4 Case Studies of CWs in Latin America

An overview of selected CW case studies in Latin America is presented in Table 21.4.

21.4.1 Brazil

The performance of HSSF-CWs planted with *Oryza sativa* L. was investigated in Campina Grande, Paraíba State, northeast Brazil. The pilot-scale system consisted of 24 circular tanks with 0.77 m diameter, 0.54 m height, batch fed daily with polluted water urban stream. Experimental units were filled with either sand or gravel and operated under HRT for 5 and 10 days. The units efficiently removed organic matter, fecal coliform, and nutrients from the influent polluted water. Vegetation was found to be the most important factor affecting their performances being the changes in both substrate and HRT investigated herein had a minor influence [42].

21.4.2 Chile

Six HSSF CWs constructed with a surface area of 2 m^2 and a depth of 0.6 m were used for the treatment of domestic wastewater. *Typha latifolia* or *Scirpus*sp. were used during the study. The units were filled with gravel or fine gravel (FG) of 2.8 and 1.2 cm in diameter, respectively. This experimental setup was evaluated over 280 days for the removal of organic matter and nutrients in a Mediterranean climate, near Valparaíso, Chile. The performance of CW for removal of COD, nutrients (NH_4^+-N and PO_4^{-3}-P), seasonal variations, and plant/support were evaluated. The *Scirpus*/FG combination showed the highest average removal of total COD of about 59%, and *Typha*/FG showed the highest removal of NH_4^+-N and PO_4^{-3}-P (49 and 32%, respectively). Additionally, the removal of COD was independent of the initial influent concentration, while mildly dependent on the season variations, unlike NH_4^+-N and PO_4^{-3}-P removal which was dependent on these two parameters. The levels of COD, ammonia, and phosphorous removal, respectively were found to be affected by the type of media, plant, and the plant-media combination [43].

21.4.3 Cuba

The treatment of pool water used for recreational or sporting purposes with CWs was tested with two VF CWs in the province of Santiago de Cuba. One of the CW was a pilot scale and the other a laboratory scale. The CWs were planted with *Typha domingensis*. When the HLR applied to the pilot scale wetland was less than 0.25 m^3/m^2/day, the levels of COD, BOD, and microbiological load in the pool water were below the maximum permissible limits of Cuban legislation. At the laboratory scale, the presence of plants favored the removal of nitrogenous compounds (ammonia and nitrates), BOD, and COD. This attitude is demonstrated by the action of microorganisms associated with the rhizome of plants or by the assimilation of organic compounds that established a symbiotic mechanism conducive to plant phytodepuration. The minimum level of ammonia emitted in the effluent of the laboratory-scale unit without a plant reached 2.15 mg/m^3. This value was within the sanitary regulation limits [44].

21.4.4 Equador

An experimental wetland study was carried out at the Wastewater Treatment Plant "El Guabo", located in Santa Isabel city, Ecuador to investigate the reduction of the economic cost of wastewater treatment and energy consumption by applying CWs and the environmental pollution. A comparison between the purification capacities of two plant species with VF was carried out in SSF CWs receiving primary treated municipal wastewater. *Cyperus Papyrus* and *Phragmites Australis* were used in the CWs. The primary treatment was carried out by a lagoon system operating at an HLR of 0.6 m^3/day. Granite gravel and silica sand were used in the lower and upper parts of the CWs, respectively. The porosity of the medium was 0.34, the HRT was 1.1 days, and the HLR was 0.2 m/day. The physico-chemical, and bacteriological characteristics of the influent and effluent wastewater were analyzed for a period of 3 months. The results for the two CWs with different plants indicated that the *Cyperus Papyrus* had a greater pollutants removal capacity for BOD (80.7%), COD (70%), NH_4-N (70%), TP (50%), TC (98.1%) and FC (95.6%), while *Phragmites Australis* retained more solids. The CW planted with *Cyperus Papyrus* showed an overall higher treatment efficiency than the other unit [45].

21.5 Conclusions

Most of the hot and arid climate countries are developing countries that also suffer from severe scarcity of water resources. In these countries, conventional wastewater treatment technologies are usually applied. However, these technologies are expensive and required skillful labor, hence they present many problems and are often not optimally operated, while no high coverage of sanitation services is so far achieved in these countries. As indicated in the past works, CWs are an efficient alternative for the sustainable treatment of different types of wastewater. CWs are simple and relatively cheap to construct and have low maintenance and operational cost. Typically, CW requires an appropriate low-cost primary treatment stage to overcome the problem of clogging. There are two major limitations for CW application: first is the required land for the construction of a CW system which is higher compared to conventional treatment methods. In hot and arid climate countries, however, land can be available at a reasonable cost. As there are many desert areas in those countries, these areas have been widely used for the construction of CWs. The second limitation is the evapotranspiration that takes place during the treatment of wastewater. However, the proper design of CW, plant species selection, and plant density can reduce the loss of water. Based on experiences from various such countries, the hybrid CW design and the vertical flow CW are the most promising choices for hot and arid climate countries.

References

1. Kadlec RH, Wallace S (2008) Treatment wetlands. CRC Press
2. Arroj MF, Haseeb F, Butt AI, Irfan-Ul-Hassan M, Batool H, Kibria S, Javed Z, Nawaz H, Asif S (2021) A sustainable approach to reuse of treated domestic wastewater in construction incorporating admixtures. J Build Eng 33:101616
3. Stefanakis AI (2020) Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. Water 12:1665. https://doi.org/10.3390/w12061665
4. Saggaï MM, Aïnouche A, Nelson M, Cattin F, El Amrani A (2017) Long-term investigation of constructed wetland wastewater treatment and reuse: selection of adapted plant species for metaremediation. J Environ Manag 201:120–128
5. Gopal B (1987) Water hyacinth, aquatic plant studies 1. Elsevier, Amsterdam
6. Gopal B (1999) Natural and constructed wetlands for wastewater treatment: potentials and problems. Water Sci Technol 40:27–35
7. El-Khateeb M, El-Bahrawy A (2013) Extensive post treatment using constructed wetland. Life Sci J 10:560–568
8. El-Khateeb M, El-Gohary F (2003) Combining UASB technology and constructed wetland for domestic wastewater reclamation and reuse. Water Sci Technol 3:201–208
9. Stefanakis AI (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability 11:6981. https://doi.org/10.3390/su11246981
10. US-EPA (2000) Constructed wetlands treatment of municipal wastewaters. Manual. US-EPA. US-EPA Report No. EPA/625/R99/010, Washington, DC
11. Stefanakis AI (2020) Constructed wetlands: description and benefits of an eco-tech water treatment system. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 503–525
12. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis AI (ed) Constructed wetlands for industrial wastewater treatment. Wiley, Chichester, pp 25–42

13. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233
14. Ramírez S, Torrealba G, Lameda-Cuicas E, Molina-Quintero L, Stefanakis AI, Pire-Sierra MC (2019) Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. Chemosphere 234:496–504
15. Díaz FJ, O'Geen AT, Dahlgren RA (2012) Agricultural pollutant removal by constructed wetlands: implications for water management and design. Agric Water Manag 104:171–183
16. Watson J, Danzig A (1992) Constructed wetlands for municipal wastewater treatment: state-of-the-art. Tennessee Valley Authority, Chattanooga
17. Brix H (1997) Do macrophytes play a role in constructed treatment wetlands? Water Sci Technol 35:11–17
18. Yuan C, Huang T, Zhao X, Zhao Y (2020) Numerical models of subsurface flow constructed wetlands: review and future development. Sustainability 12:3498
19. Benny C, Chakraborty S (2020) Continuous removals of phenol, organics, thiocyanate and nitrogen in horizontal subsurface flow constructed wetland. J Water Process Eng 33:101099
20. González AFE, Zúñiga-Benítez H, Peñuela GA (2019) Removal of herbicide 2, 4-D using constructed wetlands at pilot scale. Emerg Contam 5:303–307
21. Stefanakis AI (2020) The fate of MTBE and BTEX in constructed wetlands. Appl Sci 10(1):127. https://doi.org/10.3390/app10010127
22. Schultze-Nobre L, Wiessner A, Bartsch C, Paschke H, Stefanakis AI, Aylward LA, Kuschk P (2017) Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. Eng Life Sci 17(12):1224–1233. https://doi.org/10.1002/elsc.201600213s
23. Ghrabi A, Bousselmi L, Masi F, Regelsberger M (2011) Constructed wetland as a low cost and sustainable solution for wastewater treatment adapted to rural settlements: the Chorfech wastewater treatment pilot plant. Water Sci Technol 63:3006–3012
24. Abdel-Shafy H, Hegemann W, Teiner A (1994) Accumulation of metals by vascular plants. Environ Manag Health 5:21–24
25. Wood A, Steffen R (1999) Investigation into the application and performance of constructed wetlands for wastewater treatment in South Africa. Water Research Commission
26. Mashauri DA, Mulungu DM, Abdulhussein B (2000) Constructed wetland at the University of Dar es Salaam. Water Res 34:1135–1144
27. Okurut TO (2000) A pilot study on municipal wastewater treatment using a constructed wetland in Uganda. CRC Press
28. Nzengy'a DM, Wishitemi BL (2001) The performance of constructed wetlands for, wastewater treatment: a case study of splash wetland in Nairobi Kenya. Hydrol Process 15:3239–3247
29. Abdel-Shafy HI, El-Khateeb M, Regelsberger M, El-Sheikh R, Shehata M (2009) Integrated system for the treatment of Blackwater and greywater via UASB and constructed wetland in Egypt. Desalin Water Treat 8:272–278
30. El-Khateeb M, Al-Herrawy A, Kamel M, El-Gohary F (2009) Use of wetlands as post-treatment of anaerobically treated effluent. Desalination 245:50–59
31. Galal A, El-Gohary FA, Medhat MA, El-Khateeb MA, Mahmoud UF (2014) Treatment of drain wastewater using constructed wetlands. J Pollut Res 33:229–233
32. Kamel M, El-Khateeb M, Megahed R, Abdel-Shafy E (2010) Effect of entrance shape on the performance of constructed wetland. J Am Sci 6:787–795
33. El-Khateeb M, Kamel M, Megahed R, Abdel-Shafy E (2016) Sewage water treatment using constructed wetland with different designs. Pollut Res 35:197–201
34. Kyambadde J, Kansiime F, Dalhammar G (2005) Nitrogen and phosphorus removal in substrate-free pilot constructed wetlands with horizontal surface flow in Uganda. Water Air Soil Pollut 165:37–59
35. Laabassi A, Harzallah D, Boudehane A (2015) Performances of a constructed wetland treating planted with emergent and floating macrophytes under Algerian semi-arid climate. Carpathian J Earth Environ Sci 10:65–74

36. Møller K, Fryd O, De Neergaard A, Magid J (2012) Economic, environmental and socio-cultural sustainability of three constructed wetlands in Thailand. Environ Urban 24:305–323
37. Gurung A, Oh SE (2012) An overview of water pollution and constructed wetlands for sustainable wastewater treatment in Kathmandu Valley: a review. Sci Res Essays 7:1185–1194
38. Ebrahimi A, Taheri E, Ehrampoush MH, Nasiri S, Jalali F, Soltani R, Fatehizadeh A (2013) Efficiency of constructed wetland vegetated with *Cyperus alternifolius* applied for municipal wastewater treatment. J Environ Public Health:815962. https://doi.org/10.1155/2013/815962
39. Zeb B, Mahmood Q, Jadoon S, Pervez A, Irshad M, Bilal M, Bhatti ZA (2013) Combined industrial wastewater treatment in anaerobic bioreactor post-treated in constructed wetland. BioMed Res Int:957853. https://doi.org/10.1155/2013/957853
40. Amir H, Heidarpour M, Tarkesh-Esfahani S (2016) Evaluation of horizontal–vertical subsurface hybrid constructed wetlands for tertiary treatment of conventional treatment facilities effluents in developing countries. Water Air Soil Pollut 227:28
41. Kalankesh LR, Rodríguez-Couto S, Dadban Shahama Y, Asgarnia AH (2019) Removal efficiency of nitrate, phosphate, fecal and total coliforms by horizontal subsurface flow-constructed wetland from domestic wastewater. Environ Health Eng Manag J 6:105–111
42. Meira C, De Oliveira R, Ceballos B, Coura M, Nascimento R (2013) Warm season performance of horizontal subsurface flow constructed wetlands vegetated with rice treating water from an urban stream polluted with sewage. Afr J Biotechnol 12
43. Mancilla V, Rodrigo, Zúñiga J, Salgado E, Schiappacasse MC, Chamy Maggi R (2013) Constructed wetlands for domestic wastewater treatment in a Mediterranean climate region in Chile. Electron J Biotechnol 16:5–5
44. Guardia P, Yans, Pérez-Quintero F, Rodríguez-Pérez S, Sánchez-Girón V, Llanes-Cedeño E, Rocha-Hoyos J, Peralta-Zurita D (2019) Effect of hydraulic loading rate and vegetation on phytoremediation with artificial wetlands associated to natural swimming pools. J Water Land Dev 40:39–51
45. Fernando G, Patiño-Chávez J, Zhinín-Chimbo F, Donoso-Moscoso S, Del Pino LF, Avilés-Añazco A (2019) Performance of *Phragmites Australis* and *Cyperus Papyrus* in the treatment of municipal wastewater by vertical flow subsurface constructed wetlands. Int Soil Water Conserv Res 7:286–296