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

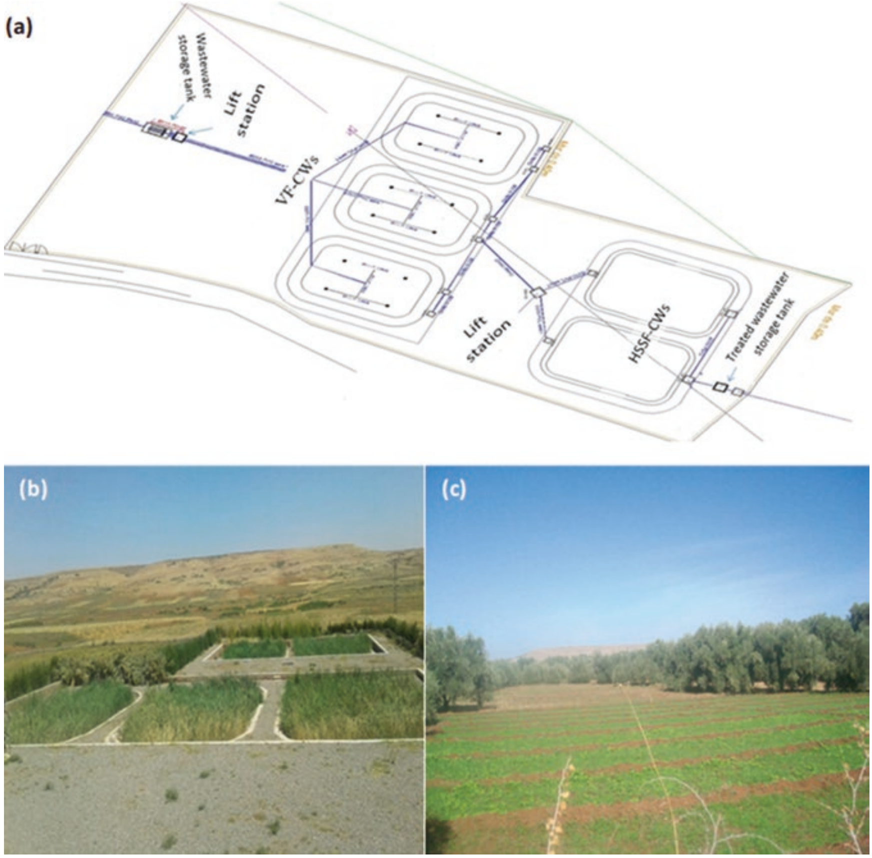

Fig. 1.2 (**a**) Schematic layout of the Tidili Mesfioua Hybrid Constructed Wetland, (**b**) aerial view of the plant, and; (**c**) field area irrigated with treated wastewater

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

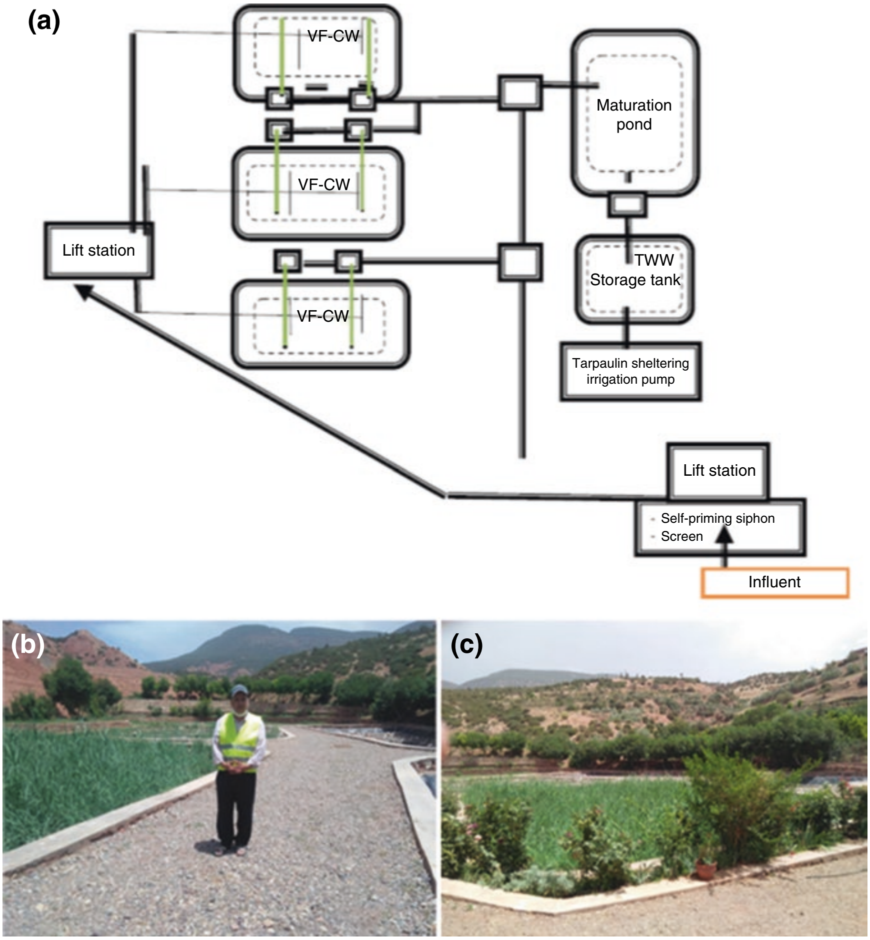

Fig. 1.3 (**a**) Schematic layout of the Asselda village's wastewater treatment plant; (**b**) aerial view of the plant and; (**c**) irrigated trees area.

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

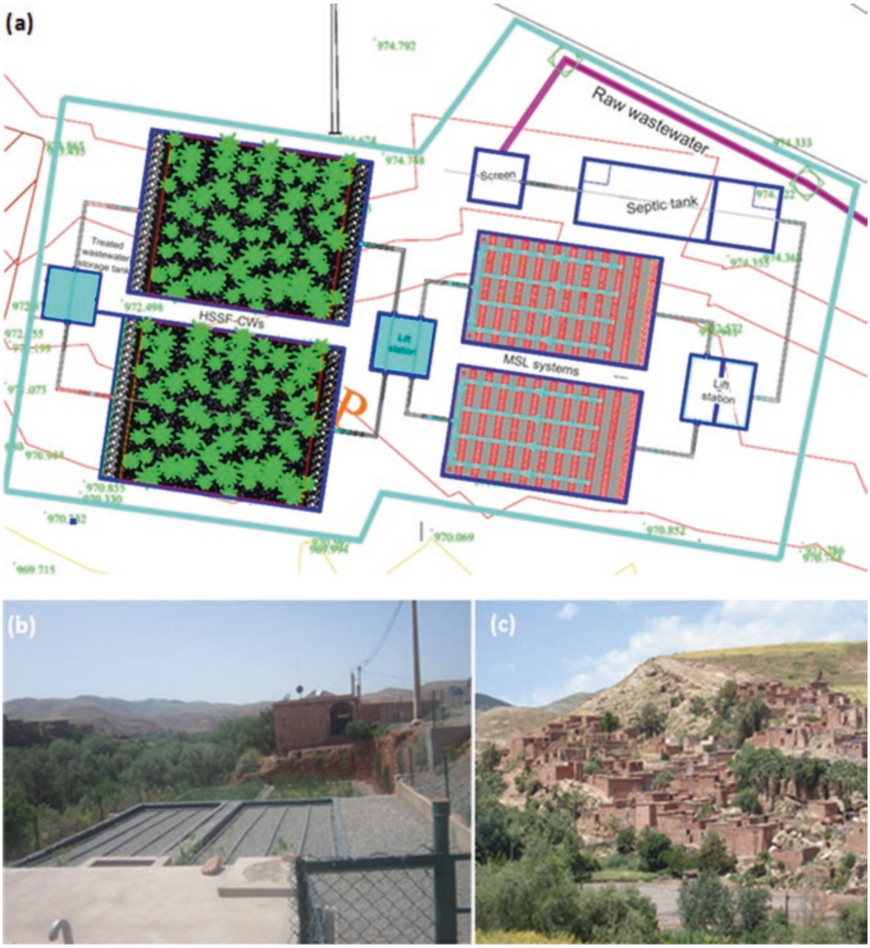

Fig. 1.4 (**a**) Schematic layout of the Talat Marghen village wastewater treatment plant; (**b**) aerial view of the plant and; (**c**) village view

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