water

MDPI

Article

Sustainable Greywater Treatment in Jordan: The Role of Constructed Wetlands as Nature-Based Solutions

Ahmed M. N. Masoud [1,*], Amani Alfarra [2], Alham W. Al-Shurafat [3] and Sabrina Sorlini [1]

[1] Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Via Branze, 43, 25123 Brescia, Italy
[2] Land and Water Division, Food and Agriculture Organization of the United Nations, 00100 Rome, Italy
[3] Climate Action Association, 28 Sa'd Bin Abi Waqqas St., Amman 11185, Jordan
* Correspondence: a.masoud@unibs.it

Abstract

Water scarcity in Jordan is intensifying, creating an urgent need for innovative approaches to maximize the use of nonconventional water resources, such as greywater treatment and reuse. This study presents a detailed analysis of the suitability of nature-based solutions (NbSs) for greywater treatment, with a focus on the application of horizontal flow constructed wetlands (HFCWs). Two systems were implemented to treat greywater generated from mosques located in Az-Zarqa Governorate, a dry region in Jordan. Following several months of operation, monitoring, and evaluation, the systems demonstrated high removal efficiencies: turbidity (>87%), total suspended solids (TSS) (>96%), chemical oxygen demand (COD) (>91%), and five-day biological oxygen demand (BOD_5) (>85%). The eight-square-meter HFCW units successfully produced one cubic meter of treated greywater per day, meeting Jordanian standards for reclaimed greywater (JS 1776:2013) for use in irrigating food crops, including those consumed raw. The system achieved a 70% reduction in water consumption compared to the same period in the year prior to its implementation. These results demonstrate the potential of constructed wetlands (CWs) as effective, low-cost, and sustainable NbSs for decentralized greywater treatment and reuse in water-scarce regions.

Keywords: nature-based solution; constructed wetlands; greywater treatment; reuse; resource recovery; water scarcity

check for updates

Academic Editors: Yingxin Shang, Zhongqing Yan, Guopeng Liang and Xueping Wang

Received: 29 June 2025
Revised: 19 August 2025
Accepted: 20 August 2025
Published: 21 August 2025

Citation: Masoud, A.M.N.; Alfarra, A.; Al-Shurafat, A.W.; Sorlini, S. Sustainable Greywater Treatment in Jordan: The Role of Constructed Wetlands as Nature-Based Solutions. *Water* **2025**, *17*, 2497. https://doi.org/10.3390/w17162497

1. Introduction

Water scarcity is a critical challenge for the Hashemite Kingdom of Jordan, influencing both its social development and economic stability [1–14]. This pressure is projected to intensify, as the population is expected to double in the coming decades—approximately 11,956 million by the end of 2025—while climate change scenarios forecast substantial reductions in the quantity and quality of available water; less than 100 m^3 of renewable water resources is available per person annually, which is below the global line for absolute water scarcity of 500 m^3 [15]. The widening gap between supply and demand threatens the sustainability of national resources and the livelihoods of future generations. One practical strategy to help alleviate this strain is the reuse of greywater, particularly in the agricultural sector.

In response, the Jordanian government has supported greywater reuse initiatives that incorporate low-cost, efficient, and environmentally sustainable treatment systems [1,2].

National standards have been established to regulate treated greywater for multiple uses, including irrigation of food crops (even those eaten raw), landscaping for public parks and playgrounds, roadside irrigation, and toilet flushing [3].

Such treatment and reuse schemes have been implemented across different settings in Jordan—from households to schools, institutional facilities, and mosques [2,4–6]. Several local and international organizations have contributed to these efforts, with the National Agricultural Research Center playing a pivotal role in expanding greywater reuse. Their activities focus on building technical capacity, conducting awareness campaigns, and piloting innovative treatment technologies.

This study applies NbSs through CWs as a low-cost, sustainable approach to greywater treatment. CWs are well-documented for their capability to treat a range of wastewater streams, yet deploying them at the community scale—particularly near residential areas—can be hindered by negative public perceptions and concerns about maintenance. Demonstrating the effectiveness of a pilot-scale NbS-CW can foster community acceptance, strengthen local technical capacity, and provide a reliable source of treated water for reuse.

Two mosques were selected as case studies, given the specific advantages they offer:

- High greywater generation: Frequent ablution generates a steady greywater flow.
- Community engagement potential: As religious and social hubs, mosques are effective platforms for promoting water reuse awareness.
- Institutional backing: Being public facilities managed by the Jordanian government, mosques offer a supportive environment for piloting and scaling NbS-CW systems.

The objectives of this research are as follows:

- To establish an alternative water source for mosque irrigation that can serve as a model for other facilities.
- To enhance public awareness and acceptance of treated greywater reuse via NbS-CWs, promoting water conservation as a climate change adaptation measure.

CWs were among the earliest NbSs applied in greywater treatment, relying on complex interactions among plants, biofilms, substrates, atmospheric oxygen, and the nutrients present in wastewater. These systems remove pollutants through the following:

- Physical processes, such as sedimentation and filtration.
- Chemical processes, including precipitation and adsorption.
- Biological processes involving microbial degradation and plant uptake [7].

Various CW configurations have been applied to greywater treatment worldwide. For instance, Collivignarelli et al. (2020) examined an HFCW and achieved removal efficiencies exceeding 92% for turbidity, >85% for TSS, >89% for COD, and >88% for BOD_5 [8]. Boopathi and Kadarkari (2022) reported HFCW efficiencies in India of 69.92–81.20% for COD, 82–91.06% for TSS, and 75.83–84.02% for total nitrogen (TN) in laboratory-scale trials [9]. Similarly, Qomariyah et al. (2022) achieved 94.13–96.84% BOD removal, 95.04–95.62% TSS removal, and 94.61–97.11% detergent removal [10]. Hachicha et al. (2022) evaluated vertical flow CWs (VFCWs) planted with Phragmites australis, finding TSS removal of $94 \pm 13\%$, COD removal of $86 \pm 5.7\%$, BOD_5 removal of $93 \pm 7\%$, ammonium reduction of $71.4 \pm 19.1\%$, total phosphorus (TP) reduction of 52%, and *E. coli* reduction of 1.24–2.40 log units [11].

Globally, CWs are increasingly recognized as integral to sustainable water management within a circular economy framework [12]. Arden et al. (2018) reviewed 13 CW applications for greywater treatment, reporting removal ranges of 63–98% for BOD_5, 64–98% for TSS, 47–97% for turbidity, 44–59% for TN, and 24–63% for TP, with 1–2 log removal for bacteria, protozoa, and viruses [13]. They also recommended incorporating disinfection to meet strict reuse standards and highlighted the P–k–C* model as a prevalent approach for CW performance modeling [13].

While much of the existing literature focuses on pilot or small-scale CW systems, relatively few studies address full-scale implementations [7]. Furthermore, research interest is growing in integrating CWs into green walls and green roofs, which involve complex biological and physico-chemical interactions influenced by the system's operating mode [14].

The findings of this study are expected to provide valuable insights into the practical application of NbS-CW systems for greywater treatment in community settings, particularly within institutional facilities such as mosques. By demonstrating the feasibility, efficiency, and social acceptance of treated greywater reuse, this research contributes to advancing sustainable water management practices in water-scarce regions like Jordan. Moreover, the results aim to inform policymakers and practitioners on scalable solutions that integrate NbSs to address water scarcity, support climate adaptation efforts, and promote environmental conservation at the local level.

2. Materials and Methods

A schematic diagram illustrating the scope of work, from water input to greywater reuse, is shown in Figure 1. The diagram summarizes the process flow, treatment steps, and removal efficiencies achieved by the implemented HFCW systems.

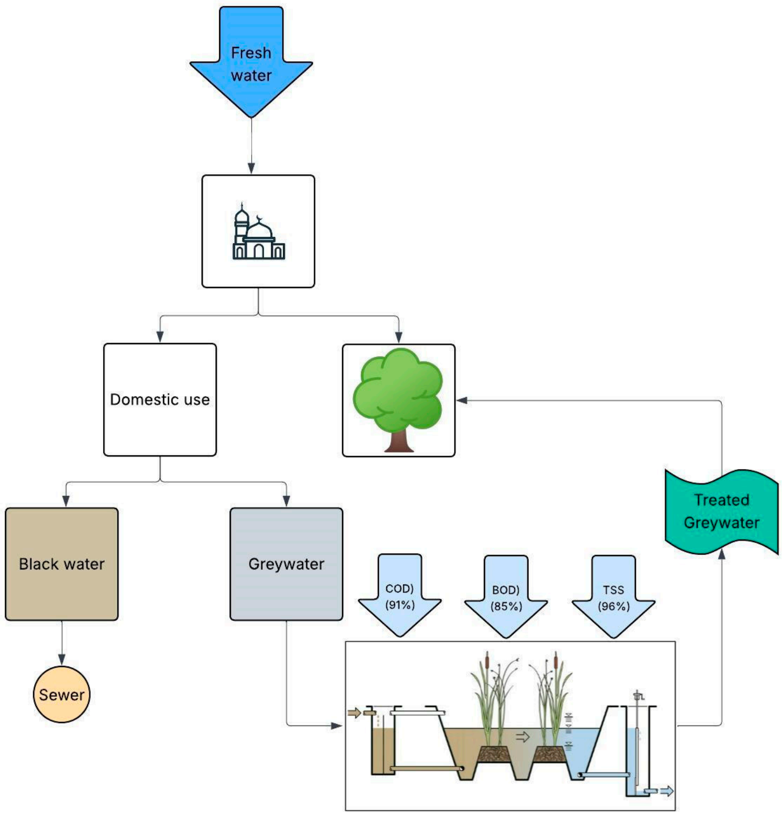

Figure 1. Scope of work and process flow for mosque greywater treatment and reuse using HFCWs.

2.1. Onsite Assessment

To identify suitable sites for implementing the NbS-CW, onsite assessments were conducted at several mosques. The first round of assessment took place between April and June 2022 for the initial pilot, and the second round occurred from November 2023 to February 2024 for the replication pilot. The assessment considered several criteria, including mosque location, building structure (single or multiple floors), the feasibility of separating greywater piping, roof availability and strength, the location of washroom facilities, the number of beneficiaries, water consumption, availability of space, and potential for water reuse.

Over fifteen mosques were evaluated. Ultimately, Abdullah Al Azab Mosque and Roqayya Bent Al Rasould Mosque, both located in Az-Zarqa Governorate, were selected. These mosques met all the established criteria. Abdullah Al Azab Mosque hosted the first pilot implementation, while Roqayya Bent Al Rasould Mosque was selected for the replication phase, aiming to validate the first pilot and expand the project impact and knowledge base.

The selection of Zarqa Governorate was strategic due to its extreme water scarcity, arid climate, and lack of vegetation. The region faces acute water shortages, making treated greywater reuse essential for sustainability. Given the limited rainfall and high evaporation rates, treated greywater reuse can support small-scale agriculture and urban greening efforts, enhancing soil quality and mitigating desertification. Additionally, Zarqa's high population density and urban infrastructure make it an ideal location for decentralized greywater treatment, offering a cost-effective and impactful solution in one of Jordan's most water-stressed regions.

2.2. Data Collection

Different data types were collected for the selected mosques, including (1) water bills, to assess water consumption and water costs; (2) the average number of daily users; (3) the number of trees and the irrigation area around the mosque; (4) greywater characteristics; (5) potential reuse options; (6) peak usage times (hour, day, and month).

2.3. Design and Preparation

The system was designed using the collected data and the raw greywater characteristics. An HFCW was selected due to its simplicity, ease of implementation and operation, and effectiveness in treating greywater, which typically has a low nitrogen load [16–18]. The literature supports the efficiency of HFCWs for greywater treatment.

The plug-flow k-C* approach was chosen to design the constructed wetland system [14,19]. As noted by Dotro et al., (2017), various design methods exist for constructed wetlands, with the plug-flow k-C* model demonstrating successful application across multiple cases [14,19].

Design guidelines from the Jordanian Standard for the Reclaim and Reuse of Treated Greywater (JS 1776/2013) was considered while designing the system [3].

The proposed treatment process included the following components: (1) a collection/sedimentation tank, (2) an HFCW, and (3) a collection tank.

Preliminary treatment typically reduces or removes solids and materials that could affect the downstream equipment or increase maintenance, using screens and a grit chamber to remove coarse debris, sand, gravel, or other heavy solid materials [14].

However, in this NbS-CW system, preliminary treatment was deemed unnecessary due to the specific characteristics of the greywater, which was primarily generated through ablution. During the feasibility study, samples were collected and analyzed, confirming that preliminary treatment could be omitted without compromising system performance.

Primary treatment [14,19,20].

Primary treatment involves the removal of suspended solids through sedimentation. Because greywater contains particulate matter denser than water, these particles settle naturally under the influence of gravity. This stage also helps to decrease the amount of suspended solids and organic matter while stabilizing the quality of greywater before it enters the constructed wetland [19,20].

In this system, the collection tank doubles as a single-chamber septic tank with a volume of one cubic meter. Septic tanks are frequently employed as a primary treatment method in small-scale constructed wetlands. To maintain effective operation, these tanks require periodic emptying once sludge and scum occupy more than 30% of the tank's liquid capacity [14,20]. Although septic tanks can typically reduce suspended solids and biochemical oxygen demand (BOD) in wastewater by approximately 50% and 30%, respectively [14], these removal efficiencies were not incorporated into the wetland design. This conservative design choice accounts for potential maintenance shortcomings and aims to improve overall system robustness.

HFCW—Plug-flow k-C*

The HFCW was designed using the plug-flow k-C* model [14,19], which considers both influent and effluent concentrations, along with an irreducible background concentration denoted as C*. This model is based on the assumptions of ideal plug-flow hydraulics. The parameter C* represents the refractory or non-biodegradable fraction of pollutants. It defines the minimum effluent concentration that can be achieved due to internal biogeochemical cycling within the wetland. Values of C* vary according to the treatment stage and are typically determined from extensive data sets, thereby establishing a theoretical lower boundary for the constructed wetland's effluent concentration (Co). Consequently, even with an infinitely long retention time, the effluent concentration Co cannot fall below C* [14,19]. Typical C* values for BOD removal are approximately 10 mg/L for primary effluent, 5 mg/L for secondary effluent, and 1 mg/L for tertiary effluent [14].

In this approach, the required wetland area (A) was calculated using Equation (1):

$$A = -\frac{Q_{in}}{k_T} ln\left(\frac{C_{in} - C^*}{C_{out} - C^*}\right) \quad (1)$$

where

A: Area of the CW [m^2];

Q*in*: Flow discharge [m^3/d];

C*in* and C*out*: Influent and target effluent concentrations [mg/L];

C*: Background concentration;

K_T: Rate coefficient (m/d) measured at T (°C), adjusted using Equation (2):

$$k_T = k_{20}\vartheta^{(T-20)} \quad (2)$$

where

k_{20} is the rate coefficient at 20 °C;

θ is the modified Arrhenius temperature factor (typically 1.06);

T is the actual water temperature in the system [°C] [14].

The area was calculated for each parameter (BOD, COD, TSS, etc.), and the largest area was used in the final design and implementation. Key design checks included the following [14,19]:

- Hydraulic Retention Time (HRT)

The hydraulic retention time (HRT, days) is

$$HRT = \frac{A \times H \times \varepsilon}{Q_{in}} \quad (3)$$

where

A is the surface area of the wetland of the CW (m^2);

H is the depth of the CW (m);
ε is the porosity of the filter material (m^3/m^3);
Q_{in} is the fixed discharge (m^3/d).

The depth of the HFCW is varied and depends on the application of the CW; for secondary treatment, the depth is between 0.35 and 0.7 m [14,19].

- The Hydraulic Loading Rate (HLR) is expressed as (m/d)

$$HLR = \frac{Q}{A} \tag{4}$$

- Mass Loading Rates (ML) [kg/m^2d] represent the amount of mass loaded into the CW daily and can be calculated as

$$ML = \frac{Q \times C_{in}}{A} \tag{5}$$

- The Cross-Sectional Organic Loading Rate (CSL) ($gBOD_5/m^2d$) is fundamental to avoiding clogging problems during the operation. It is measured as

$$CSL = \frac{BOD_{5,in}}{CS} \tag{6}$$

where BOD_5 is the biochemical oxygen demand load (BOD_5) (g/day) entering the CW tank and CS (m^2) is the cross-sectional area determined by

$$CS = W \times H \tag{7}$$

where W is the wetland's width (m) and H is the saturated depth (m).

The CSL is a fundamental parameter to monitor in order to avoid clogging issues during operation. It should not exceed 250 $gBOD_5/m^2/d$ [19]. The recommended HF-CW length-to-width ratio (L:W) ranges between 2:1 and 4:1. Additionally, a longitudinal slope base of 1% is advised to facilitate drainage and prevent water stagnation [14,19].

Design guidelines and manuals from the literature were reviewed to define system limits and ensure efficient performance. Table 1 summarizes key design thresholds adopted from different resources [14,19].

Table 1. Design limits for CWs [14,19].

Parameter	Free Water Surface CW	Vegetated Submerged CW
Organic loading rate (kg BOD/ha day)	5–110	10–200
Nitrogen loading rate, kg N/ha. day (Kg/ha day)	0.5–60	2–80
HRT (d)	3–10	2–7
HLT (cm/d)	2.5–10	2.5–20
Water depth from the surface (cm)	20–50	2–10
L:W	4:1–6:1	2:1
Bed depth (cm)	-	30–90

Finally, it is possible to estimate the efficiency of pollutant removal by plants using the simplified equation

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \tag{8}$$

where η represents the removal efficiency, C_{in} is the influent concentration, and C_{out} is the effluent concentration.

2.4. Filter Media Selection

Several functions are served by filter media in CWs. They provide support for vegetation roots, facilitate the distribution and collection of flow at the inlet and outlet, offer surface area for microbial colonization, and act as physical filters to trap suspended particles [14,19,21,22]. Hydraulic conductivity is reduced by very fine particles, which can also promote surface flow, whereas very large particles allow higher flow rates but offer limited microbial surface area. Additionally, large and angular materials may impede root growth. Therefore, intermediate-sized materials—typically gravel—are recommended. This gravel should be thoroughly double-washed to eliminate fine particles that might clog the system's void spaces [14,19,21].

In HFCWs, filter media sizes generally range from 0.2 mm to 40 mm [14,19,21,22]. Larger media sizes of 40 to 80 mm are advised for inlet and outlet zones to reduce clogging risks and are applied throughout the full depth of these zones. Within the treatment zone, no significant difference in pollutant removal efficiency has been observed for media sizes between 10 and 60 mm [14,19,21,22].

2.5. Monitoring

Sampling and testing were carried out by local expert engineers from the partner NGO, Climate Action Association (CAN), following the sampling procedures in "STANDARD METHODS FOR THE EXAMINATION OF WATER AND WASTEWATER, 23RD EDITION" [23]. Laboratory analyses were performed at the Water, Energy, and Environment Center at the University of Jordan and Water Authority of Jordan laboratories [23].

3. Results

3.1. Assessment and Mosque Selection

More than fifteen mosques were assessed in three cities: Amman, Zarqa, and Irbid. Among these, Abdullah Al Azab Mosque was identified as the most suitable location for the first pilot project, while Roqayya Bent Al Rasoul Mosque was selected to replicate and validate the initial implementation. Both mosques are located in Zarqa city, in the eastern part of Jordan, which is characterized by a semi-arid to arid climate, receiving less than 250 mm of rainfall annually, typically in brief, infrequent events [24].

The mosques are connected to the municipal drinking water network, which supplies freshwater used primarily for domestic use, ablution, and for irrigating the mosques' gardens. The water bills are covered by the Ministry of Awqaf and Religious Affairs, which frequently leads to increased consumption rates. For drinking purposes, bottled water is commonly used, a widespread practice in Jordan. Water demand varies during the year, peaking in the summer months (July to September). The highest usage period is during Ramadan, with Friday afternoons (coinciding with the main prayer time) representing the weekly peak.

The total land area of Abdullah Al Azab Mosque is approximately 2154 m^2, of which 540 m^2 is covered with vegetation, comprising 65 different species of trees and herbs. In comparison, Roqayya Bent Al Rasoul Mosque occupies around 3900 m^2, with only 550 m^2 planted with 35 trees. The limited extent of vegetation at both sites is primarily attributed to water availability constraints. Weekly water consumption for irrigation is estimated to range between 6 and 9 m^3 at Abdullah Al Azab Mosque and can reach up to 10 m^3 at Roqayya Bent Al Rasoul Mosque. Manual surface irrigation methods are currently employed at both locations.

Figure 2 shows the top view of Abdullah Al Azab Mosque's facilities, and Figure 3 shows the layout of Roqayya Bent Al Rasoul Mosque.

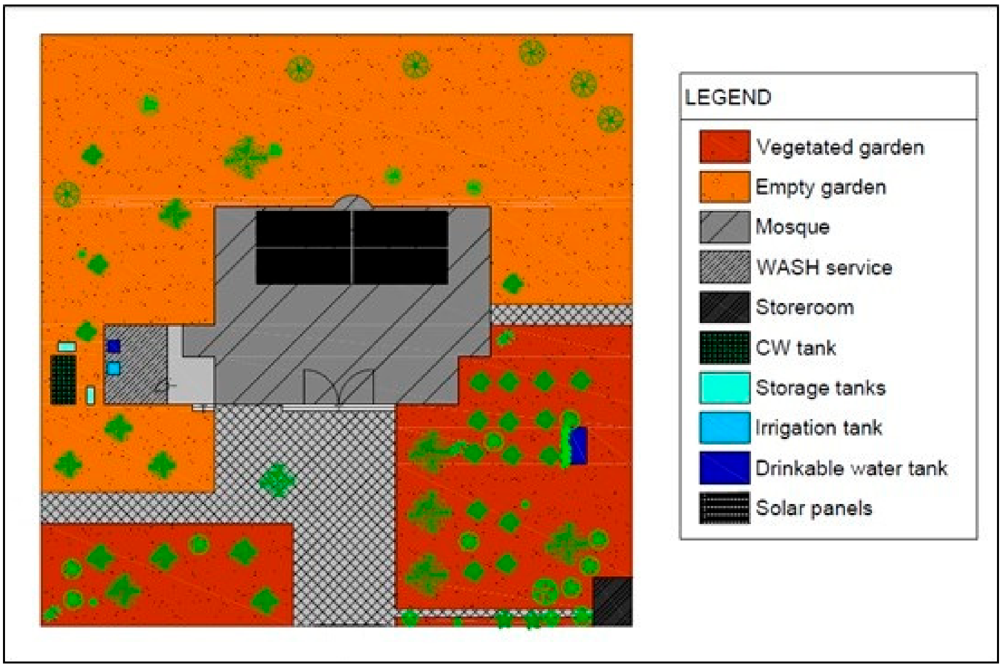

Figure 2. Abdullah Al Azab Mosque: top view sketch.

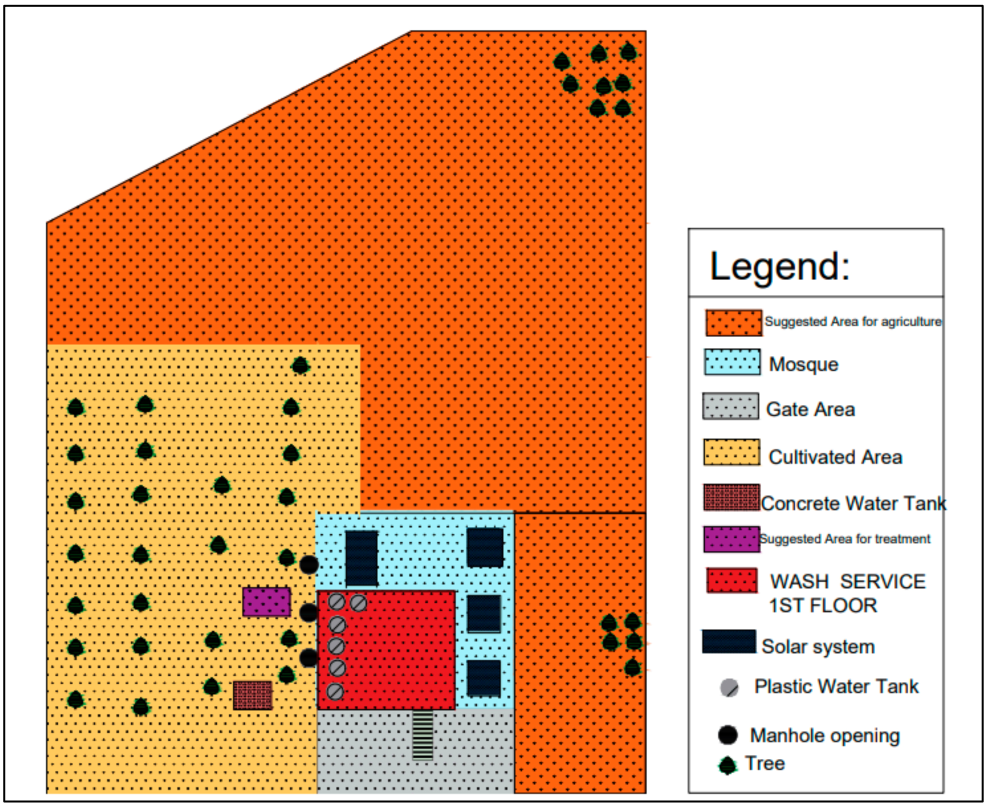

Figure 3. Roqayya Bent Al Rasoul Mosque: top view sketch.

A key opportunity was identified in the reuse of treated greywater for irrigating the existing garden. Furthermore, the availability of treated water provides the potential for expanding vegetated areas, thereby supporting environmental enhancement and water conservation at the mosque level.

3.2. Data Collections

A summary of water consumption in the mosques for the last three years is illustrated below in Tables 2 and 3. Water usage is limited to ablution practices, toilet flushing, and garden irrigation. The recorded water consumption is relatively high. Implementing treated greywater reuse has the potential not only to reduce overall water consumption but also to expand green areas through the irrigation of additional plants and vegetation.

Table 2. Water consumption—Abdullah Al Azab Mosque.

Year	Duration	Water Consumption (m^3)	Cost (JOD)
2020	First Quarter	45	23.0
	Second quarter	200	409.3
	Third quarter	68	53.5
	Fourth quarter	217	462.4
2021	First Quarter	108	141.7
	Second quarter	97	113.6
	Third quarter	326	791.6
	Fourth quarter	99	118.7
2022	First Quarter	147	251.0

Table 3. Water consumption—Roqayya Bent Al Rasoul Mosque.

Year	Duration	Water Consumption (m^3)	Cost (JOD)
2021	First Quarter	-	-
	Second quarter	165	305.4
	Third quarter	155	275.2
	Fourth quarter	-	-
2022	First Quarter	122	177.4
	Second quarter	178	344.6
	Third quarter	173	329.5
	Fourth quarter	235	515.8
2023	First Quarter	235	515.8
	Second quarter	282	658.7
	Third quarter	336	821.78
	Fourth quarter	50	86.7

The collected data will be utilized to estimate the water savings achieved following the implementation and operation of the CWs.

3.3. Detailed Design

3.3.1. Raw Greywater Characterization

To inform the design of the HFCW, the characteristics of the raw greywater were initially determined. Composite samples were collected over three consecutive days (1 to 3 June 2022 for Abdullah Al Azab Mosque and from 15 to 18 December for Roqayya Bent Al Rasoul Mosque) and then tested and analyzed in a certified laboratory. The resulting data reflect typical greywater characteristics generated at both mosques, which were found to be nearly identical in quality.

Table 4 shows the average values of key raw greywater parameters used in the HFCW design. Among all parameters analyzed, TSS and BOD_5 were prioritized in the treatment design, as they represent the most critical indicators affecting system performance and effluent quality.

Table 4. Raw greywater characteristics.

Parameter	Unit	Raw Greywater Abdulla Al Azab	Raw Greywater Roqayya Bent Al Rasoul
BOD	mg/L	100	100
COD	mg/L	170	153
TSS	mg/L	200	195
NH_4	mg/L	less than 4.4	less than 5
NO_3^-	mg/L	12.96	13
Turbidity	NTU	15.9	16
Temperature	C	25	25

3.3.2. Design Targets and Reuse Standards

The target effluent concentrations for the treated greywater were determined according to JS 1776/2013 [3]. Table 5 summarizes the required effluent limits for the reuse of treated greywater. Given the project objectives, the reuse option selected for the treated greywater is irrigation of food crops intended for human consumption, including those consumed raw.

Table 5. Jordanian standard for greywater reuse [3].

Parameter	Cooked Vegetables, Parks, Playgrounds, and Roadsides Within Cities	Food Crops Intended for Human Consumption, Including Raw Consumption	Toilet Flushing
BOD_5 (mg/L)	60	60	<10
COD (mg/L)	120	120	<20
TSS (mg/L)	100	100	<10
pH	6–9	6–9	6–9
NO_3^- (mg/L)	70	70	70
TN (mg/L)	50	50	50

The proposed NbS aims to meet or exceed these quality thresholds to ensure safe and sustainable reuse.

3.3.3. Flow Assumptions

The daily greywater inflow from both mosques is estimated at 1.1 cubic meters per day (m^3/d). Although greywater generation peaks during prayer times and religious events, the design flow was selected conservatively to reflect average daily production and align with budget constraints. This flow rate also supports the objective of maximizing treated water reuse potential for productive and safe applications.

Using Equation 1, two areas were calculated: one required a reduction in BOD from 100 to 60 mg/L, and another a decrease in TSS from 200 to 100 mg/L.

The area A required for BOD and TSS removal is calculated using the plug-flow equation:

$$A = \frac{Q}{Kt} In\left(\frac{Cin - C^*}{Cout - C^*}\right)$$

where

Q = flow rate (1.1 m^3/day);

Kt = areal rate constant adjusted to temperature;

Cin, Cout = influent and effluent concentrations;

C* = background concentration (depending on the pollutants).

C* can be calculated for the BOD and TSS with the same equations using different constant values, according to Abdel Razik Zidan and Mohammed Abdel Hady (2018) [25], as follows:

$$C^*_{BOD} = 3.5 + 0.053 \times \ C_{BOD,in} \tag{9}$$

$$C^*_{TSS} = 5.1 + 0.16 \times C_{TSS,in} \tag{10}$$

Therefore, the background concentration C* was determined to be 8.8 mg/L for BOD and 37.1 mg/L for TSS:

$$C^* = 5.1 + 0.16 \times 200 = 37.1 \text{ mg/L}$$

Usually, C* values for BOD range from 1 to 10 mg/L, depending on the treatment stage (i.e., primary, secondary, or tertiary), while C* for TSS is commonly around 37 mg/L [14,19,21,26]. These values are influenced by several factors, including the wastewater temperature, the initial concentration of the raw wastewater, and the treatment stage [19].

The removal coefficient rate K_{20} was selected and adjusted according to water temperatures, following the methodology described in [14,19].

The design parameters and the final calculated areas for the selected parameters (BOD and TSS) are summarized in Table 6.

Table 6. Design parameters and the final calculated areas.

Parameter	K_{20} (m/y)	Q (m^3/day)	T (°C)	K_t (m/y)	C_{in} (mg/L)	C* (mg/L)	C_{out} (mg/L)	A (m^2)	Expected η (%)
BOD	37	1.1	25	37.0	100.0	8.8	60.0	6.3	40
TSS	30	1.1	25	48.3	200.0	37.1	100.0	7.9	50

A filter material depth of 50 cm was selected, with water depths maintained below the surface at 10 cm at the inlet and 20 cm at the outlet [19]. Jordanian volcanic tuff was chosen as the filter medium. This material has been recommended in several studies for its porous texture, which creates a conducive environment for microbial growth [19]. Additionally, tuff is locally available at a low cost (cost-effective).

The media used in all the CW tanks have a porosity (ε) of 0.60 [27], and the length-to-width ratio (L:W) was set at 2:1.

The final dimensions of the HFCWs were selected accordingly and are summarized in Table 7 below. A freeboard of 0.3 m was added to the total depth of the HFCW to ensure safe operation.

Table 7. Final dimensions of the HFCW.

HF-CW Tank Size	
High (m) (including 0.3 m free board)	0.8
Width (m)	2.0
Length (m)	4.0
Area (m^2)	8.0
Volume (m^3)	6.4

The determined CSL is below the maximum value recommended in the literature, which is 250 $gBOD_5/m^2/day$ [$gBOD_5/m^2d$].

Other design parameters, including HRT, HLR, ML, and CSL, have been calculated and verified accordingly. The results are summarized in Table 8 below.

Table 8. Design parameter check.

AREA (m^2)	Saturated Depth (m)	ε (porosity)	HRT (d)	HLR (m^3/d)	ML—BOD (kg/ha.d)	CSL Rate ($gBOD_5/m^2d$)
8.00	0.4	0.6	1.8	0.14	13.75	137.5

The design parameters were found to comply with the recommended limits previously outlined in Table 1 [14,19], particularly regarding hydraulic retention time (HRT). In accordance with the operational requirements of the constructed wetland, a dosing system was installed to deliver greywater from the collection tank to the wetland during daytime hours. This dosing system is adjustable to optimize treatment efficiency. During the initial operational phase, dosing was configured to supply 0.1 m^3 every two hours, based on the availability of greywater in the collection tank.

Three prefabricated polyethylene water tanks, each with a capacity of 1 m^3, were employed in the project. The functions of these tanks are as follows:

- The first tank serves as a collection/sedimentation unit for the raw greywater.
- The second tank receives the treated greywater from the HFCW.
- The third tank fully stores the treated greywater, which is connected to the irrigation network.

The HFCW was implemented using a prefabricated galvanized steel tank, internally isolated with polyethylene sheets. The inflow and outflow configurations were carefully designed to ensure uniform water distribution across the entire HFCW bed, avoiding dead zones.

The filter media within the HFCW were distributed as follows:

- The first and last 40 cm of the tank length were filled with coarse volcanic tuff, with a diameter of 4 cm.
- The central 3.2 m were filled with tuff of 2 cm in diameter.

The inlet pipe was positioned 10 cm below the surface of the tuff, while the outlet pipe was installed 20 cm below the tuff surface to ensure proper flow direction. The bed was designed with a 1% slope slanting towards the outlet.

Phragmites australis was planted in the wetland, with distances of 25 cm to 50 cm between each reed.

The design also includes a recirculation system that provides several benefits:

- It dilutes raw greywater with treated greywater.
- It maximizes reuse, enabling the storage and recirculation of treated water when direct reuse is not required.
- It maintains water levels in the CW, supporting optimal performance.

To ensure system safety and resilience, the following overflow mechanisms were included:

- The first tank has an overflow connection to the sewer system, ensuring smooth discharge by gravity in case of overloading or pump failure.
- The second tank includes an overflow outlet that directs excess treated greywater to irrigate trees, as the quality at this stage is suitable for reuse.
- An additional overflow from the final collection tank on the rooftop is connected to the first collection tank, completing the recirculation loop.

3.4. Monitoring Plan, Laboratory Details

The initial pilot system began operating on 1 July 2022. One month after commissioning, a structured monitoring program commenced assessment of system performance across different seasonal and climatic conditions. Monitoring included sampling at two key points: (i) the inlet (first collection tank), representing raw greywater, and (ii) the outlet (second tank), representing treated effluent post-CW treatment.

Sampling and analysis were conducted monthly for four months, aligning with standard wastewater monitoring protocols. The methodologies followed the procedures outlined in the "Standard Methods for the Examination of Water and Wastewater, 23rd Edition" [22]. Laboratory testing was performed by the Water, Energy, and Environment Center at the University of Jordan and Water Authority of Jordan laboratories. This adherence to established methodologies ensures data reliability and comparability.

Table 9 presents the removal efficiencies across the monitoring period. The CW demonstrated excellent performance in reducing key pollutants. TSS removal ranged from 93% to 100%, BOD_5 from 70% to 93%, COD from 88% to 93%, and turbidity consistently exceeded 90% reduction after the initial round. Notably, the pH remained within the acceptable range throughout, and *E. coli* levels dropped significantly, with the best observed removal efficiency reaching 72%.

Table 9. Removal efficiencies for the main parameters—HFCW, 1st mosque.

Parameter	**1 August**			**2 September**			**5 October**			**12 November**		
	Raw	**Treated**	**Efficiency**	**Raw**	**Treated**	**Efficiency**	**Raw**	**Treated**	**Efficiency**	**Raw**	**Treated**	**Efficiency**
BOD_5 (mg/L)	100	30	70%	57	4	93%	91	9	90%	84	10.1	88%
COD (mg/L)				146	17	88%	160	12	93%	139	11.3	92%
TSS (mg/L)	200	6	97%	183	12	93%	156	5	97%	138.7	0	100%
pH		8		7.3	8.3		7.1	7.8		7.2	7.6	
NO_3^- (mg/L)	13	12.28	6%	36	24	33%	31	23	26%	39	27	31%
TN (mg/L)				39	30	23%	36	26	28%	41	29	29%
Turbidity NTU	16	7	56%	57	3	95%	16	0	100%	17	0	100%
E. coli (MPN/100 mL)		<1		763	213	72%	661	190	71%	310	146	53%
Helminth eggs (egg/L)				NA	NA	-	NA	NA		NA	NA	
FOG (mg/L)				NA	NA	-	NA	NA		NA	NA	

Note: NA: Not available (not detected).

The observed reduction in nitrate and TN was more variable, aligning with findings in the previous literature that CWs typically show moderate nitrogen removal unless optimized with specialized plant or substrate configurations [14,18,25]. Despite this, most parameters met the Jordanian greywater reuse standard (JS 1776:2013) for use in irrigating crops consumed raw as illustrated in Table 10 below [3]. However, reuse for toilet flushing may require additional disinfection to comply with stricter *E. coli* and turbidity requirements.

Table 10. Parameters for the treated greywater vs. reuse limits, 1st mosque.

Parameter	**Treated Greywater**				**Food Crops Intended for Human Consumption, Including Raw Consumption**
	1 August	**2 September**	**5 October**	**12 November**	
BOD_5 (mg/L)	30	4	9	10.1	60
COD (mg/L)		17	12	11.3	120
TSS (mg/L)	6	12	5	0	100
pH	8	8.3	7.8	7.6	6–9
NO_3^- (mg/L)	12.28	24	23	27	70
TN (mg/L)		30	26	29	50
Turbidity NTU	7	3	0	0	undefined
E. coli (CFU/100 mL)	<1	213	190	146	1000
Helminth eggs (egg/L)		NA	NA	NA	<1
Fat, Oil, & Grease (FOG) (mg/L)		NA	NA	NA	8

For the second pilot project, which commenced in January 2024, similar testing protocols were adopted. Three monitoring rounds (March, July, and October 2024) reaffirmed the CW's effectiveness. BOD_5 removal ranged from 91% to 97%, COD from 91% to 96%, and TSS reached 100% removal in two out of three tests. Turbidity consistently dropped to zero, and *E. coli* was reduced by 93% in October, indicating substantial pathogen removal capacity.

Although data for parameters such as Helminth eggs and FOG were not always available, prior studies indicate that CWs, especially when vegetated with species like Phragmites australis, are effective in reducing such pollutants [11,13,21].

Mara et al. (2003) suggest that post-treatment polishing units or disinfection (e.g., chlorination or UV treatment) are often recommended for applications requiring low pathogen counts [28]. Future system optimization could include such units, particularly for urban settings where the public health risk is more sensitive.

For the second pilot project, the same testing process was implemented, but for three rounds of testing, and the results are illustrated in the same way in Tables 11 and 12 below.

Table 11. Removal efficiencies for the main parameters—HFCW, 2nd mosque.

Parameter	1 March 2024			2 July 2024			5 October 2024		
	Raw	Treated	Efficiency	Raw	Treated	Efficiency	Raw	Treated	Efficiency
BOD_5 (mg/L)	397	20	95%	458	16	97%	186	16	91%
COD (mg/L)	496	43	91%	610	24	96%	243	22	91%
TSS (mg/L)	23	0	100%	64	18	72%	13	0	100%
pH	7.22	8		7.31	7.39		6.9	7.7	
NO_3^- (mg/L)									
TN (mg/L)									
Turbidity NTU	12	0	100%	14	0	100%	13	0	100%
E. coli (MPN/100 mL)							2310	163	93%
Helminth eggs (egg/L)				NA	NA	-	NA	NA	
FOG (mg/L)				NA	NA	-	NA	NA	

Note: NA: Not available (not detected).

Table 12. Parameters for the treated greywater vs. reuse limits, 2nd mosque.

Parameter	1 March	2 July	5 October	Food Crops Intended for Human Consumption, Including Raw Consumption
BOD_5 (mg/L)	20	16	16	60
COD (mg/L)	43	24	22	120
TSS (mg/L)	0	18	0	100
pH	8	7.39	7.7	6–9
NO_3^- (mg/L)				70
TN (mg/L)				50
Turbidity NTU	0	0	0	undefined
E. coli (CFU/100 mL)			163	1000
Helminth eggs (egg/L)		NA	NA	<1
Fat, Oil, & Grease (FOG) (mg/L)		NA	NA	8

Note: NA: Not available (not detected).

3.5. Water Saving

An evaluation of water savings was carried out at Abdullah Al Azab Mosque using historical water billing data. Post implementation monitoring showed a substantial decrease in potable water usage. During the July to September 2022 period, consumption was 97 m^3 (cost of JOD 113.63) compared to 326 m^3 (cost: JOD 791.60) for the same period in 2021. This represents a 70% reduction in water usage and an 85% decrease in cost (Figure 3).

This reduction aligns with the estimated 1 m^3/day treated greywater output from the CW, confirming that most of the mosque's irrigation needs were met with reclaimed water. This outcome reflects not only the system's technical performance but also the community's acceptance and behavioral changes resulting from awareness-raising efforts.

At Roqayya Bent Al Rasould Mosque, similar trends were observed. Starting from January 2024, water consumption decreased significantly, with treated greywater being utilized to irrigate the olive trees previously left unwatered. These results highlight the potential of NbS-CWs to significantly reduce water demand in institutional settings (Figure 4).

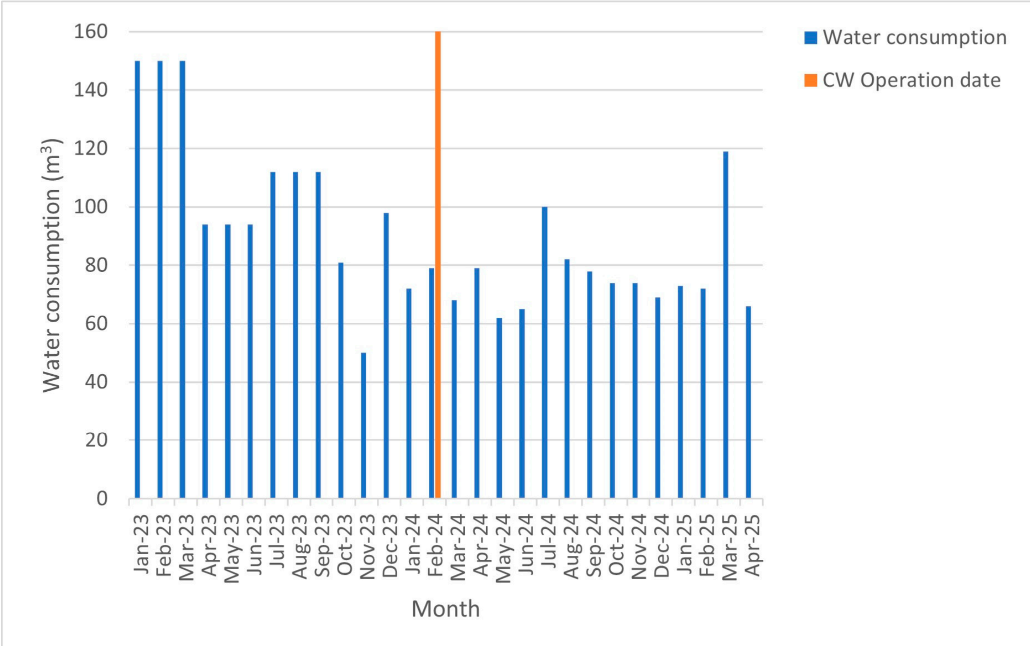

Figure 4. Water consumption—before and after the HFCW.

CW systems thus serve as practical, replicable solutions that address both environmental and economic dimensions of water management. Their integration into public facilities can help Jordan move closer to meeting national water efficiency goals, as outlined in the Water Sector Strategic Plan [29].

4. Discussion and Conclusions

There is a great demand for and a growing interest in nonconventional water resources in water-scarce countries such as Jordan. Several projects and funds have been developed to invest in and define sustainable options for treating and reusing greywater, which have been supported and controlled by Jordanian policies and standards.

This study demonstrates the viability and effectiveness of using HFCWs as NbSs for decentralized greywater treatment and reuse in water-scarce environments like Jordan. The dual case study approach, focusing on two mosques in Az-Zarqa Governorate, has highlighted both the technical performance and socio-economic impact of the system.

From a technical standpoint, the CW systems consistently demonstrated high removal efficiencies of key pollutants such as BOD_5, COD, TSS, turbidity, and pathogens across multiple testing periods and climatic conditions. These results meet or exceed national reuse standards (JS 1776:2013) for agricultural irrigation, reinforcing the validity of HFCWs as low-tech, sustainable, and robust treatment options. Their use of local materials such as volcanic tuff further enhances cost-effectiveness and replicability.

Socially, the integration of greywater treatment within mosque premises promoted community acceptance, facilitated behavioral change, and encouraged a culture of water stewardship. Awareness campaigns and stakeholder engagement played a vital role in overcoming initial skepticism, especially regarding public health concerns. The reuse of treated water for irrigation visibly improved mosque gardens and strengthened the perceived value of the intervention.

Economically, the greywater reuse system delivered significant financial benefits by reducing freshwater consumption and associated utility bills, achieving up to 85% cost savings during peak seasons. While exact investment costs were not measured in this study, the main construction expenses were related to excavation, concrete works, volcanic tuff media, the CW bed, piping, and planting. Operational costs are minimal, limited mainly to pumping, which, in these cases, is powered by existing solar photovoltaic systems at the mosques. Potential technical challenges may include clogging from inappropriate waste disposal in the greywater drains, accumulation of solids due to infrequent sedimentation tank cleaning, and possible vandalism, as the systems are located in publicly accessible areas. These risks can be mitigated through provision of operation and maintenance training and guidance manuals to operators, regular sediment removal, and community awareness sessions to promote proper system use. The minimal maintenance requirements, combined with the passive treatment process and reliance on gravity flow, make these systems particularly well-suited to under-resourced or rural contexts. The results of this study also resonate with Jordan's broader national goals, such as those outlined in the National Water Strategy (2016–2025), which prioritizes nonconventional water sources, cost-effective water supply solutions, and climate adaptation measures. Moreover, this research contributes to global discussions on sustainable urban water management, circular economy principles, and NbSs, as highlighted in recent UNEP frameworks [30].

These findings align closely with other studies from Jordan and arid regions. For example, Abunasera and Abdelhayb (2020) demonstrated a vertical flow constructed wetland in rural Jordan, achieving ~90% removal for BOD, COD, and TSS, with effluent meeting irrigation standards [1]. Hybrid CWs treating pharmaceutical wastewater in Jordan achieved over 98% removal of specific micropollutants while complying with industrial reuse standards as found by Saeed et al., 2023 [31]. Studies in similar arid climates done by Albalawneh et al., 2016 and Ammari et al., 2014, the studies confirm the robust treatment performance of horizontal and recirculated vertical flow wetlands [32,33]. These parallels reinforce the applicability and effectiveness of our mosque-based HFCWs in water-scarce environments.

Nevertheless, the study recognizes certain limitations and avenues for future improvement. These include the need for the following:

- Long-term monitoring to understand seasonal and operational variability;
- Quantification of sludge generation and its management;
- Consideration of advanced treatment (e.g., UV, chlorination) for sensitive reuse applications;
- Design refinement for nitrogen and phosphorus removal.

Incorporating solar-powered pumps, automated dosing, or smart monitoring systems could further optimize performance and enhance resilience, particularly in the face of climate variability.

In conclusion, this study not only validates the technical and economic feasibility of HFCWs for greywater treatment but also illustrates their broader value as tools for community engagement, water conservation, and climate resilience. These systems hold significant potential for replication and scaling, not only across Jordan but also in other semi-arid and arid regions globally.

Author Contributions: Conceptualization, A.M.N.M. and A.W.A.-S.; methodology, A.M.N.M.; formal analysis, A.M.N.M. and A.W.A.-S.; writing—original draft preparation, A.M.N.M.; data curation, A.M.N.M.; writing—review and editing, A.W.A.-S., S.S., and A.A.; supervision, S.S. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the implementation were funded by Fondazione Sipec Brescia, Italy, and Agriculture and Agrifood Canada through the Food and Agriculture Organization of the United Nations.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. Some data are not publicly available due to confidentiality and privacy agreements with the organization where the research was conducted.

Acknowledgments: The Italian Agency for Development Cooperation has supported this study, and the Jordanian NGO Climate Action Association (CAN) received the funds and facilitated the implementation of the pilot in Jordan.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Abdelhay, A.; Abunaser, S.G. Modeling and Economic Analysis of Greywater Treatment in Rural Areas in Jordan Using a Novel Vertical-Flow Constructed Wetland. *Environ. Manag.* **2021**, *67*, 477–488. [CrossRef] [PubMed]
2. Al Arni, S.; Elwaheidi, M.; Salih, A.A.M.; Ghernaout, D.; Matouq, M. Greywater Reuse: An Assessment of the Jordanian Experience in Rural Communities. *Water Sci. Technol.* **2022**, *85*, 1952–1963. [CrossRef] [PubMed]
3. *JS 1776/2013*; JSMO Reclaimed Graywater. JSMO: Amman, Jordan, 2013.
4. Al-Mashaqbeh, O.A.; Ghrair, A.M.; Megdal, S.B. Grey Water Reuse for Agricultural Purposes in the Jordan Valley: Household Survey Results in Deir Alla. *Water* **2012**, *4*, 580–596. [CrossRef]
5. Masoud, A.M.N.; Belotti, M.; Alfarra, A.; Sorlini, S. Multi-Criteria Analysis for Evaluating Constructed Wetland as a Sustainable Sanitation Technology, Jordan Case Study. *Sustainability* **2022**, *14*, 14867. [CrossRef]
6. Qdais, H.A.; Abdulla, F.; Kurbatova, A. Wastewater Reuse in Jordan and Its Potential as an Adaptation Measure to Climate Change. *J. Environ. Eng. Sci.* **2019**, *14*, 203–211. [CrossRef]
7. Boano, F.; Caruso, A.; Costamagna, E.; Ridolfi, L.; Fiore, S.; Demichelis, F.; Galvão, A.; Pisoeiro, J.; Rizzo, A.; Masi, F. A Review of Nature-Based Solutions for Greywater Treatment: Applications, Hydraulic Design, and Environmental Benefits. *Sci. Total Environ.* **2020**, *711*, 134731. [CrossRef] [PubMed]
8. Collivignarelli, M.C.; Miino, M.C.; Hernan Gomez, F.; Torretta, V.; Rada, E.C.; Sorlini, S. Horizontal Flow Constructed Wetland for Greywater Treatment and Reuse: An Experimental Case. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2317. [CrossRef] [PubMed]
9. Boopathi, N.; Kadarkarai, R. A Laboratory-Scale Study of Residential Greywater Treatment with Sugarcane in a Constructed Wetland. *Environ. Sci. Pollut. Res.* **2022**, *29*, 61178–61186. [CrossRef] [PubMed]
10. Qomariyah, S.; Utomo, B.; Wahyudi, A.H. Constructed Wetlands with Cyperus Alternifolius as a Sustainable Solution for Household Greywater Treatment. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1065*, 012025. [CrossRef]
11. Hachicha, R.; Fersi, M.; Jedidi, N.; Mechichi, T.; Hassen, A.; Hachicha, R. Graywater Treatment with Two Planted Vertical Constructed Wetlands in Series: A Pilot Study. *Clean* **2022**, *50*, 2100118. [CrossRef]
12. Masi, F.; Rizzo, A.; Regelsberger, M. The Role of Constructed Wetlands in a New Circular Economy, Resource Oriented, and Ecosystem Services Paradigm. *J Environ. Manag.* **2018**, *216*, 275–284. [CrossRef]
13. Arden, S.; Ma, X. Constructed Wetlands for Greywater Recycle and Reuse: A Review. *Sci. Total Environ.* **2018**, *630*, 587–599. [CrossRef]
14. Kadlec, R.H.; Wallace, S.D. *Treatment Wetlands*; CRC Press: Boca Raton, FL, USA, 2009; ISBN 9781566705264.
15. MWI. *Jordan Water Sector, FACTS and Figures*; MWI: Amman, Jordan, 2022.
16. Masoud, A.M.N.; Alfarra, A.; Sorlini, S. Constructed Wetlands as a Solution for Sustainable Sanitation: A Comprehensive Review on Integrating Climate Change Resilience and Circular Economy. *Water* **2022**, *14*, 3232. [CrossRef]
17. Stefanakis, A.I. The Role of ConstructedWetlands as Green Infrastructure for Sustainable Urban Water Management. *Sustainability* **2019**, *11*, 6981. [CrossRef]
18. Avery, L.M.; Frazer-Williams, R.A.D.; Winward, G.; Shirley-Smith, C.; Liu, S.; Memon, F.A.; Jefferson, B. Constructed Wetlands for Grey Water Treatment. *Ecohydrol. Hydrobiol.* **2007**, *7*, 191–200. [CrossRef]
19. Dotro, G.; Langergraber, G.; Molle, P.; Nivala, J.; Puigagut, J.; Stein, O.; von Sperling, M. *Biological Wastewater Treatment Series, Volume 7: Treatment Wetlands*; IWA Publishing: London, UK, 2017; Volume 7, ISBN 9781780408774.
20. UN-HABITAT UN-HABITAT. Constructed Wetlands Manual. In *UN-HABITAT Water for Asian Programme Nepal, Kathmandu*; United Nations Human Settlements Programme: Kathmandu, Nepal, 2008; ISBN 9789211319637.
21. Stefanakis, A.; Akratos, C.S.; Tsihrintzis, V.A. *Vertical Flow Constructed Wetlands: Eco-Engineering Systems for Wastewater and Sludge Treatment*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2014.
22. Arias, C.A.; Amin, L.; Ananthatmula, R.; Andrews, L.; Baxpehler, H.; Behrends, L.L.; Bresciani, R.; Brodnik, U.; Buttiglier, G.; Castañares, L.; et al. *Nature-Based Solutions for Wastewater Treatment*; IWA Publishing: London, UK, 2021.
23. Baird, R.B.; Rice, C.E.W.; Eaton, A.D. *Standard Methods for the Examination of Water and Wastewater*, 23rd ed.; American Public Health Association (APHA), American Water Works Association (AWWA), Water Environment Federation (WEF): Washington, DC, USA, 2017.

24. MWI. *Jordan Water Sector—Facts and Figures*; MWI: Amman, Jordan, 2017.
25. Zidan, A.R.A.; Hady, M.A.A. *Constructed Subsurface Wetlands Case Study and Modeling*; CRC Press: Boca Raton, FL, USA, 2018; ISBN 9781315365893.
26. Merriman, L.S.; Hathaway, J.M.; Burchell, M.R.; Hunt, W.F. Adapting the Relaxed Tanks-in-Series Model for Stormwaterwetland Water Quality Performance. *Water* **2017**, *9*, 691. [CrossRef]
27. Al Dwairi, R.A.; Al Saqarat, B.; Shaqour, F.; Sarireh, M. Characterization of Jordanian Volcanic Tuff and Its Potential Use as Lightweight Aggregate. *Jordan J. Earth Environ. Sci.* **2018**, *9*, 127–133.
28. Mara, D. *Domestic Wastewater Treatment in Developing Countries*; Routledge: London, UK, 2003.
29. MWI. *National Water Strategy 2016–2025*; MWI: Amman, Jordan, 2016.
30. *United Nations Environment Programme Nature-Based Solutions for Wastewater Management*; United Nations Environment Programme: Nairobi, Kenya, 2021.
31. Al-Mashaqbeh, O.; Alsalhi, L.; Salaymeh, L.; Dotro, G.; Lyu, T. Treatment of Pharmaceutical Industry Wastewater for Water Reuse in Jordan Using Hybrid Constructed Wetlands. *Sci. Total Environ.* **2024**, *939*, 173634. [CrossRef] [PubMed]
32. Abunaser, S.G.; Abdelhay, A. Performance of a Novel Vertical Flow Constructed Wetland for Greywater Treatment in Rural Areas in Jordan. *Environ. Technol* **2020**, *41*, 1–11. [CrossRef] [PubMed]
33. Ammari, T.G.; Al-Zu'bi, Y.; Al-Balawneh, A.; Tahhan, R.; Al-Dabbas, M.; Ta'any, R.A.; Abu-Harb, R. An Evaluation of the Re-Circulated Vertical Flow Bioreactor to Recycle Rural Greywater for Irrigation under Arid Mediterranean Bioclimate. *Ecol. Eng.* **2014**, *70*, 16–24. [CrossRef]