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# Development of a Constructed Wetland for Greywater Treatment for Reuse in Arid Regions: Case Study in Rural Burkina Faso

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**Abstract:** This study implemented and assessed, over a period of four weeks, a full-scale constructed wetland designed to collect and treat the greywater for a rural household located in an arid environment typical of Africa's Sahel region. The system was constructed from local materials and consisted of a shower room, a receiving basin, a pre-treatment filter, and a subsurface horizontal flow wetland planted with *Chrysopogon zizanioides*. Results showed the overall removal of organic matter was greater than 90%, and orthophosphate and ammonium were reduced by 73% and 60%, respectively, allowing for the treated water to retain some embedded nutrients. The removal efficiency of fecal bacteria varied from 3.41 (enterococci) to 4.19 (fecal coliforms) log10 units which meets World Health Organization Guidelines for restricted irrigation. Our assessment of the full-scale household constructed wetland technology adds to the relatively low number of constructed wetland studies conducted outside a laboratory setting. Furthermore, it supports efforts to promote safe reuse of an underutilized resource at the rural household level in Sub-Saharan Africa and other arid regions in the developing world, supporting prospects for using treated greywater for agricultural reuse in regions that experience water scarcity, climate variability, and land degradation.

**Keywords:** greywater reuse; pathogens; drought; climate; food security; water reuse guidelines

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## 1. Introduction

In low- and middle-income countries, access to adequate sanitation services is still a major challenge despite efforts made over the past several decades. For example, greywater, which is households' wastewater without feces, is most often discharged untreated onto streets and into open stormwater drains [1,2]. This unsanitary disposal practice is partially responsible for the transmission of a large number of water-related diseases such as malaria and diarrhea. In fact, in low- and lower-middle income countries, diarrhea accounts for more than 90% of under-five children death from which 88% are located in Southern Asia and Sub-Saharan Africa [3].

In addition, Sahelian countries are facing an increasing demand for freshwater resources due to population growth and the effects of climate change [4]. Because of increasing demand for fresh vegetables, water reuse for agriculture is becoming increasingly important. Indeed, many studies report on wastewater reuse for agriculture in different parts of the world [4–6], and 10% of the world's population is estimated to consume wastewater-irrigated foods [7].

In rural Africa, one source of wastewater is households' greywater generated from several activities [1]. For example, in rural Burkina Faso, greywater is generated from three main sources (laundry, dishwashing, and shower) with a production of 8 to 13 L per capita per day [1] and up to 43.36 ± 17 L per capita per day in urban areas of Ghana [2]. In this context, reusing greywater in agriculture at the household level could be beneficial for increasing food security and nutrition through the production of vegetables. However, greywater generated in these rural areas may not be safe. Indeed, several studies have reported the presence of high contents of microorganisms (*Escherichia coli*, fecal coliforms, enterococci, and *Salmonella* spp.) and nutrients in greywater [2,8,9] that could negatively impact human health and the environment.

Implementing on-site greywater treatment systems at the household level can repurpose an underutilized source of water and can be an effective solution to overcome water scarcity and local pollution while allowing for the non-potable reuse of treated greywater in agriculture. Constructed wetlands (CWs) are considered a simple, sustainable, and cost-effective technology [10] with economic and societal benefits that can even include access to green space [11]. Overviews of different types of CWs and the factors that influence their treatment performance for chemical and microbial pollutants have been covered elsewhere [12–15]. This includes the expected removal of different types of pathogens [16]. There has also been research over the past decade on new technologies that could be added to CWs to enhance performance [17,18]. However, many technologies such as membrane separation may not be entirely feasible for widespread application in rural areas, especially in low- and middle-income countries [15].

Horizontal wetlands (the focus of this study) have been observed to run the risk of bed clogging under high loading rates of organic matter and suspended solids (SS). Furthermore, concentrations of fecal indicator bacteria in CW effluent have been reported to be exponentially related to their loading rate [19]. Greywater is typically less concentrated with these pollutants than blackwater except in some instances where children's feces end up in greywater from hygiene activities. In the context of increasing food production in rural households, CWs have been studied for their potential to support food production and agricultural reuse [20,21] and could be an effective technology for greywater treatment, although the effluent must be tested to ensure it meets safe reuse standards. Use of planted systems is reported to improve removal rates of microbial constituents [22,23]. Furthermore, the removal of nitrogen is known to be greater in vertical flow wetlands [24], though horizontal flow CWs have an advantage for irrigation of fields and gardens because the wastewater will retain embedded nitrogen required by plants.

Unfortunately, a recent analysis to determine the global regions where most greywater research originates clearly showed the lack of research originating from Sub-Saharan Africa [6] when compared to high-income countries. Nevertheless, in rural areas with similar context to our research study, several challenges must be overcome, specifically the collection of multiple greywater sources generated within a household in order to have sufficient quantity for gardening, the transfer of collected greywater using gravity and then through the treatment system without the need for the input of mechanical energy, the need to use locally available materials to ensure affordability, and the lack of data in this particular context.

As such, this study implemented and assessed a constructed wetland for greywater treatment (using locally available materials) that requires no mechanical energy and allows the collection of all greywater sources generated in a rural household for repurposed reuse in gardening. Furthermore, the treatment system was assessed for its efficiency in terms of organic matter, nutrient, and microbial removal. This research is important for several reasons. Research on the performance of CWs outside of a laboratory setting is limited with less than 10% of studies identified in a recent review performed in the field [25]. In addition, untreated greywater reuse in irrigation is thought to be common in many parts of Sub-Saharan Africa [26]. Because of the possible presence of pathogens and microorganisms carrying antimicrobial resistance genes in greywater [27–29], this reuse option is considered as a higher-risk activity [26]. Furthermore, the technology assessed in this research can enhance safe greywater reuse in arid parts of the developing world such as the Sahel region, a fragile semiarid region in Africa that experiences water scarcity, climate variability, and land degradation [30]. Finally, because locally produced greywater is recognized as an underutilized resource in many parts of the world, there is a need to better understand the type of system that is most likely to encourage safe greywater reuse [31,32].

## 2. Materials and Methods

### 2.1. Study Site

This study was conducted in a household of the rural settlement of "Noungou" (N 12°12′7″; W 1°18′31″) located in the rural commune of "Koubri" in the central region of Burkina Faso. The household was composed of 8 persons of which 2 were under 5 years old. The site is located in the Sudano-Sahelian zone that experiences two contrasting seasons: an eight-month dry season from October to May and a four-month rainy season from June to September. The rainiest months of the year are July and August, and the average annual rainfall is 788 mm. Temperature varies between 17 and 45 °C with an annual average of 28.2 °C [33].

### 2.2. Development of the Constructed Wetland

A literature review [1,2,10,34], site visits, and observations were used to determine the activities generating greywater and to estimate the per capita quantity. The data collected were used to design the greywater treatment system. For example, from a study conducted in two rural settlements in Burkina Faso, the per capita greywater productions were estimated at 8 and 13 L per capita per day [1]. This would result in 64 to 104 L of greywater per day for a rural household of eight individuals. With the final objective being to promote the safe reuse of the treated greywater for household gardening, four issues were addressed during the development of the treatment unit: (1) The system should be constructed of locally available materials. (2) The shower was found to be the major source of greywater (56–70%) in rural households [1]; this greywater is currently poured directly onto the ground and flows out of the courtyard. Therefore, the shower room should be adapted to allow for the collection of shower greywater, and the treatment system should be close to the shower room but outside of the courtyard. (3) Dishwashing and laundry greywater are collected in containers and reused for the same activities inside the courtyard. An alternative solution should be proposed to allow the conveyance of these sources of greywater to the treatment system while avoiding the need to carry the containers outside of the courtyard where the treatment system will be located. (4) In order to allow the reuse in gardening, the treated greywater collected in a final receiving tank should meet World Health Organization (WHO) guidelines related to the treated effluent water quality (*E. coli* $< 10^5$ CFU/100 mL) [7]. The sources of greywater treated in this study were from the three household activities: showering, laundry, and dishwashing.

A literature review [34,35] suggested the treatment system should have two stages of treatment: (1) a first stage, considered as a pre-treatment phase, is expected to reduce the content of organic matter, and (2) a second stage should be a planted filter because of the expected contribution of plants in the removal of microbial pollutants.

### 2.3. Design and Set-Up of the Complex Shower Room Greywater Treatment System

The greywater management facility (Figure 1) is composed of three main components: a shower room, a receiving basin, and a greywater treatment system developed using locally available materials (plastic tanks, local plants, concrete, and granitic gravel and sand as filter media). The design of the shower room was based on the system reported previously by Maiga et al. [36] with slight modifications to allow for the collection of shower greywater that then flows to the treatment system using gravity. Issues related to laundry and dishwashing greywater collection are solved by integrating a receiving basin (internal L × W × H: 0.7 m × 0.5 m × 0.3 m) for collection of laundry and dishwashing greywater, connected to the shower room and located inside the courtyard. After laundry and dishwashing activities, the collected greywater is discharged into this basin, from where it can flow to the treatment system located outside the courtyard, through the same pipe as the shower greywater. To ensure that the entire study took place under real conditions, the system was operated in batch mode, receiving greywater as soon as it was produced by a user in the household.

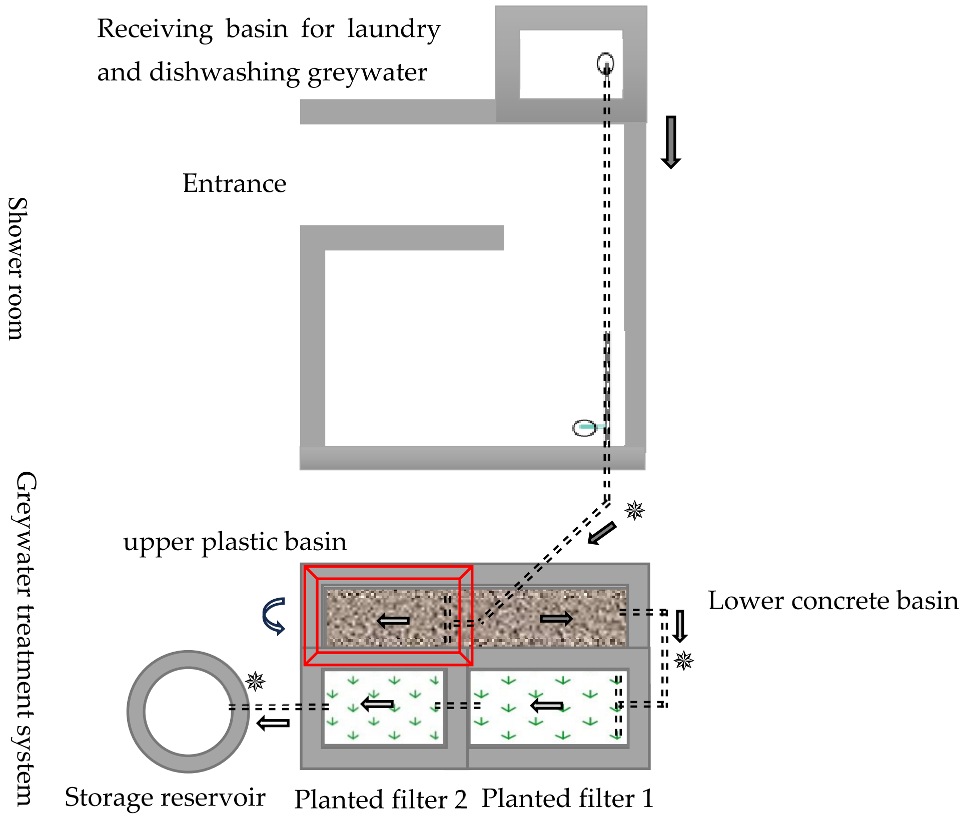


**Figure 1.** Schematic top view of the complex shower room greywater treatment system. ❋: sampling location; ⟹: greywater flow circuit (top of figure to bottom); = = = = =: greywater direction.

The treatment system is a subsurface horizontal flow wetland with an upstream pre-treatment step. The design is based on the following references [34–38] and our previous study characterizing the physicochemical and microbiological quality of greywater in rural areas [1]. Each filter media was washed with tap water and dried before packing it into the filter. Pre-treatment consists of two superimposed compartments. The first level is a plastic tank (internal L × W × H: 1.00 m × 0.60 m × 0.35 m) containing 0.15 m of crushed granite of 2–6 mm grain size. The second level is a basin made of concrete (internal L × W × H: 2.00 m × 0.40 m × 0.30 m) and filled with the same granitic gravel at a height of 0.15 m. The planted section is semi-underground and made of concrete with internal dimensions of L × W × H of 2.00 m × 0.50 m × 0.75 m. It is crossed by a wall of 0.2 m allowing two compartments in series (internal L × W × H: 1.00 m × 0.50 m × 0.75 m and 0.80 m × 0.50 m × 0.75 m) communicating through an orifice. The two compartments are filled with sand (0.50–2.00 mm) at a height of 0.45 m and planted with *Chrysopogon zizanioides* (5 plants/m$^2$). This plant (a perennial grass of the *Poaceae* family) was selected based on its vigorous and deep root system that makes it ideal for use in planted filters, in soil remediation, and in erosion control [39]. In addition, a study demonstrated its influence in increasing treated greywater quality compared to unplanted filters [35]. Finally, the treated greywater is collected in an underground storage reservoir of 200 L capacity. More details on the design of the treatment unit can be found in Supplementary Materials [37,38].

### 2.4. Monitoring of the Greywater Treatment System

After four weeks of operation, the facility was assessed in terms of its ability to treat greywater. In developing countries, in a water reuse option, priority should be allocated to the removal of organic matter (Chemical Oxygen Demand [COD], 5-day Biochemical Oxygen Demand [$BOD_5$]) and pathogen removal [40]. Therefore, to ensure the proper operation of the system, the performance was evaluated through weekly monitoring of water quality parameters for organic matter and fecal indicators such as *E. coli*, fecal coliforms, and enterococci. Nutrients ($NH_4^+$, $NO_3^-$, and $PO_4^{3-}$) which are beneficial for plants were included in the water quality analysis because of the proposed agriculture reuse of the treated greywater.

Raw, pre-treated, and treated greywater samples were collected from three sampling locations from the treatment system (Figure 1) once a week for eight weeks. Just before the entrance to the plastic box (first level of pre-treatment), the greywater collection pipe is fitted with an extension sloping downwards by around 30 degrees, which collects the raw greywater as it passes through the main pipe. Accordingly, the collected influent may be a mixture of shower greywater, laundry greywater, and dishwashing greywater or mainly from one of the three sources. After the pre-treatment step, just before entering the planted filter, the drainage pipe is fitted with a device for collecting the pre-treated greywater. This device is similar to the one used for raw greywater collection. The treated greywater is collected directly from the storage reservoir. Procedures related to sample collection and storage were followed according to the Standard Methods for the Examination of Water and Wastewater [41].

During the collection of the greywater samples, parameters such as pH, electrical conductivity (EC), and temperature (T °C) were measured *in situ* using a portable pH/EC/TDS/Temperature meter (Hanna, Romania). Dissolved Oxygen (DO) was determined in situ using an Oxymeter Oxi 3310 (WTW Germany GmbH, Wuppertal, Germany). The organic matter was evaluated through the determination of COD, $BOD_5$, and Suspended Solids [SS], and nutrients such as nitrate, ammonium, and orthophosphate were determined according to the Standard Methods for the Examination of Water and Wastewater [41]. The spread plate method was used to evaluate fecal coliforms and *E. coli* using Chromocult Coliform Agar ES medium (Merck KGaA, Darmstadt, Germany) at 44 °C for 24 h. Enterococci were assessed using the Slanetz and Barthley agar medium (Liofilchem srl, Roseto degli Abruzzi, Italy) at 37 °C for 48 h. The microbial parameters were also determined according to the Standard Methods for the Examination of Water and Wastewater [41]. Physicochemical and nutrient water quality parameters were determined for the influent and the effluent greywater while microbial and organic pollutants were measured at all three sampling locations.

### 2.5. Data Analysis

The analysis of data was conducted using Microsoft Excel version 2010 and XLSTAT software version 2016. The treatment efficiency (*TE* in%) of the physicochemical parameters (organic matter and nutrient) and the removal efficiency (*RE* in log10 units) of fecal bacteria were calculated using Equations (1) and (2), respectively:

$$TE(\%) = \left(\frac{X0 - X}{X0}\right) \times 100 \tag{1}$$

$$RE\ (log10\ units) = log\ (X0) - log\ (X). \tag{2}$$

In these two equations, $X0$ and $X$ equal the concentration of a given water quality parameter in the influent and the effluent greywater, respectively. The concentrations of organic matter, nutrients, and fecal bacteria in treated and untreated greywater were compared using a *t*-test at a significance level of 0.05. A Pearson correlation analysis was performed to determine the relationship between the concentrations of several parameters and their removal efficiency.

## 3. Results and Discussion

### 3.1. Appearance of the Greywater Treatment System during the Operation Phase

Visual observation of the treatment system indicated it performed as described in the following text. Shower greywater (including urine) percolated directly into the upper basin of the pre-treatment stage. Dishwashing and laundry greywater poured into the receiving basin (located inside the courtyard) and passed through the same piping to the treatment system. The plants (*C. zizanioides*) used in the filters appeared healthy and we observed growth throughout the experimental phase (via visual observation), showing the plants' ability to withstand the greywater conditions (Figure 2).

**Figure 2.** Complex shower room greywater treatment system planted with *C. zizanioides* under operation. (**a**) Beginning of study and (**b**) three months after operation began. Greywater flow and system components are shown on Figure 1.

### 3.2. Characteristics of Influent and Effluent Greywater

The results showed that the organic matter (SS, $BOD_5$, and COD) and nutrient ($NH_4^+$, $NO_3^-$, and $PO_4^{3-}$) contents of the influent greywater are high and varied during the study period (Table 1). These concentrations decreased as greywater passed through the treatment system (Table 1). The high organic matter content in greywater was previously attributed to heavy detergent, food, and cloth waste associated with the laundry and kitchen [42].

**Table 1.** Average water quality parameters of treated, pre-treated, and untreated greywater (values in mg/L except temperature (°C), pH, EC (mS/cm), *E. coli*, fecal coliforms, and enterococci (CFU/100 mL).

| Parameter [1] | Raw Greywater | Pre-Treated Greywater | Treated Greywater | WHO/FAO Guidelines |
|---|---|---|---|---|
| T °C | 28.11 (1.63) $^a$ | nd | 28.10 (1.80) $^a$ | - |
| pH | 8.01 (0.53) $^a$ | nd | 8.40 (0.22) $^a$ | 6.5–9.00 * |
| EC | 5.84 (2.67) $^a$ | nd | 2.38 (0.60) $^b$ | <3.00 mS/cm * |
| DO | 0.31 (0.16) $^a$ | nd | 0.44 (0.17) $^a$ | - |
| SS | 2273.75 (1287.08) $^a$ | 401.25 (291.62) | 47.50 (16.69) $^b$ | <50 mg/L * |
| $BOD_5$ | 2867.86 (1185.46) $^a$ | 500.75 (422.98) | 71.83 (40.13) $^b$ | - |
| COD | 4264.25 (2403.38) $^a$ | 1235 (1080.95) | 306.00 (147.76) $^b$ | - |
| $NH_4^+$ | 439.38 (184.24) $^a$ | nd | 158.00 (128.71) $^b$ | - |
| $NO_3^-$ | 90.65 (79.76) $^a$ | nd | 9.46 (7.36) $^b$ | - |
| $PO_4^{3-}$ | 21.60 (12.41) $^a$ | nd | 6.91 (5.06) $^a$ | - |
| *E. coli* | $2.84 \times 10^7$ ($2.98 \times 10^7$) $^a$ | $8.17 \times 10^5$ ($1.61 \times 10^6$) | $1.49 \times 10^4$ ($1.90 \times 10^4$) $^b$ | $<10^5$ *E. coli*/100 mL ** |
| Fecal coliforms | $2.15 \times 10^9$ ($3.12 \times 10^9$) $^a$ | $6.89 \times 10^7$ ($1.9 \times 10^8$) | $1.36 \times 10^5$ ($1.87 \times 10^5$) $^a$ | - |
| Enterococci | $4.47 \times 10^7$ ($5.23 \times 10^7$) $^a$ | $2.13 \times 10^5$ ($3.16 \times 10^5$) | $8.75 \times 10^3$ ($1.37 \times 10^4$) $^b$ | - |

Notes: $n = 8$ except for $PO_4^{3-}$ ($n = 4$). EC: electrical conductivity; SS: suspended solids; nd: not determined; ( ): standard deviation. [1] For a given parameter, influent and effluent values with different superscript letters are significantly different. * FAO guidelines [43]. ** WHO Restricted irrigation: relaxed to $<10^6$ when exposure is limited [7].

The temperature of the raw and treated greywater reached 28.00 °C (Table 1). These values are consistent with the generally reported range of 18 to 30 °C for greywater reported in developing countries [34] and are suitable for microbial growth. The pH of the greywater was slightly alkaline and slightly increased across the treatment train (Table 1); however, it remained within the range of the FAO guidelines for wastewater reuse in agriculture set between 6.50 and 9.00 [43]. The EC of our raw greywater was high, most likely because of the presence of urine from the shower room. It was significantly reduced to a much lower value after passing though the treatment system ($t$-test at $\alpha < 0.05$). The DO value was low and slightly increased after the treatment (Table 1).

The average concentration of nutrients (439.38 mg/L for ammonium for instance) and fecal bacteria ($2.84 \times 10^7$ CFU/100 mL for *E. coli*) in the raw greywater are high (Table 1). This is most likely because of the presence of children under 5 years of age. In fact, in rural areas like in this study, families do not use diapers and wash fecal-contaminated clothes, leading to higher concentrations of nutrients and fecal bacteria in the greywater [44]. Nevertheless, Table 1 shows that these water quality parameters decreased significantly after the raw greywater passed through the treatment system. Indeed, the concentrations of nutrients ($NH_4^+$ and $NO_3^-$) and fecal bacteria (*E. coli* and enterococci) are significantly higher in the influent than their values in the effluent ($t$-test at $\alpha < 0.05$).

### *3.3. Microbial Removal Efficiency*

At the end of the pre-treatment step, the average removal efficiency was greater than 1.5 log10 units for all fecal indicators. Except for *E. coli*, the contribution of the pre-treatment phase to the removal of fecal bacteria was slightly higher than that of the planted section (Figure 3). This situation can be explained by several factors including the microbial loading associated with the influent, because adsorption and precipitation occur with the solid substrate as the greywater passes through the pre-treatment phase. This observation is supported by Wu et al. [19] who reported in a review that the removal of microbial species is exponentially related to the loading rate. The removal efficiency increased to 3.45 and 3.41 log10 units for *E. coli* and the enterococci and up to 4.19 log10 units for fecal coliforms (Figure 3) as the greywater passed through the whole treatment system. The observed residual *E. coli* content in the treated effluent was lower than 5 log10 units, consistent with the WHO guidelines suggested for greywater reuse in restricted irrigation [7].

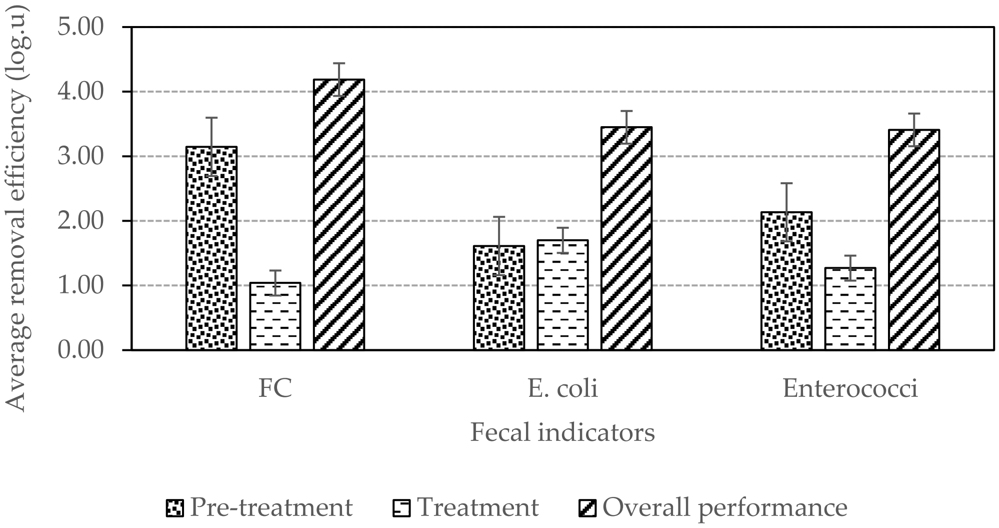


**Figure 3.** Removal efficiency of fecal indicators after the pre-treatment, the planted filter, and the entire greywater treatment system. FC: Fecal coliforms; Pre-treatment: from sampling location 1 to location 2; Treatment: from sampling location 2 to location 3; Overall Performance: from sampling location 1 to location 3.

Maiga et al. [16] discuss the key factors and strategies to enhance pathogen removal in constructed wetlands (including horizontal flow CWs). A lower removal efficiency of 2.8 log10 units for fecal coliforms has been reported by Arden and Ma [42] from a review of studies using a horizontal subsurface constructed wetland for greywater treatment. CWs with emergent vegetation are expected to have greater removal of bacteria than systems that are not planted [22] and the hydraulic residence time (HRT) appears to be a primary factor affecting removal of fecal indicators [45]; however, a subsurface wetland will not provide the solar disinfection expected in a free water surface CW [46]. In fact, constructed wetlands are generally capable of providing up to 2 to 5 log10 units removal for bacteria depending on the wetland type (vertical, free water surface, horizontal, green roof water cycle system, etc.) [42] and the initial concentration of bacteria in the raw greywater.

The relatively high removal efficiency observed in our study was for a low-cost system made of local materials commonly found in a developing world setting. The removal efficiency could be partly related to the high initial bacterial concentration of our raw greywater (Table 1) as previously observed with wastewater [47]. Also, our system employs several mechanisms known to be responsible for the removal of bacteria in constructed wetlands; that is, physical filtration by adsorption onto filter media, biofilm or plant roots, sedimentation of particle-associated bacteria, biological antagonistic actions (attack by bacteriophage, predation by protozoa, and potential production of bactericidal compounds or antimicrobial activity of root exudates) [42,47] and natural die-off. For example, bacteria can attach to granular media and plant root surfaces and subsequently become trapped with biofilms [47]. Furthermore, biofilms can act as filters that trap or sequester suspended solids-associated bacteria.

The performances achieved by the treatment system are interesting in terms of microbial removal, but it should be improved to further reduce the bacterial content of the treated greywater. This could be accomplished by integrating a sunlight-based disinfection section through the use of a shallow pond [46,48]. However, this section should be designed to prevent mosquito breeding.

### *3.4. Removal of Organic Matter*

The treatment efficiency (TE) for organic matter (SS, $BOD_5$, and COD) was observed to be greater than 70% after the pre-treatment phase. The contribution of the planted section to removal was approximately the same as that of the pre-treatment phase (Figure 4). However, it may be greater than the reported values since the raw greywater used as influent for the pre-treatment contained more pollutants than the influent used for the planted section. Indeed, Wu et al. [49] observed a positive correlation between COD loading rate and COD removal rate.

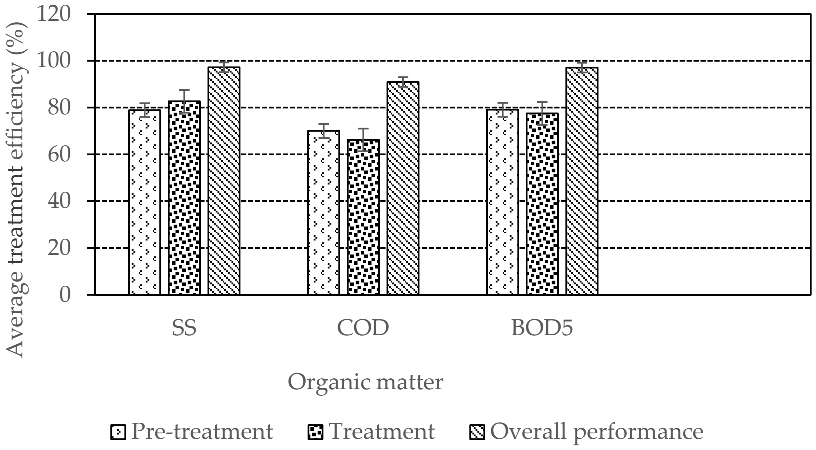


**Figure 4.** Mean treatment efficiencies of organic matter after the pre-treatment phase, the treatment, and the entire greywater treatment system. Pre-treatment: from sampling location 1 to location 2; Treatment: from sampling location 2 to location 3; Overall Performance: from sampling location 1 to location 3.

The TE values were increased to more than 90% (97, 91, and 97% for SS, COD, and $BOD_5$, respectively) when the entire greywater treatment system was considered (Figure 4). A similar trend was obtained in another study employing planted wetlands of *Phragmite karka* treating municipal wastewater with values of 91.3 and 90.5% for SS and $BOD_5$ removal, respectively [50]. However, Arden and Ma [42] reported lower removal efficiencies of 64 and 87% for SS and $BOD_5$, respectively. This difference could be explained by the influence of environmental operating conditions in cold and warm climates. Considering the fact that BOD5 removal is a biological process and that microbial metabolic activity in wetlands is affected by temperature [51], warmer temperature values in the Sahelian region may explain the removal rates being higher in our study compared to the data collected in colder climates.

The removal mechanisms for organic matter in horizontal flow constructed wetlands include physical processes of filtration and sedimentation (filter media) and biological processes (aerobic and anaerobic metabolism), as well as chemical processes [44]. The presence of plants could have enhanced the treatment efficiencies obtained in our study. Indeed, an increase in the treatment efficiency of organic matter was previously obtained when a planted wetland was compared to an unplanted filter [35,50]. The authors also reported that the type of plant used in the wetland can influence the treatment efficiency. *C. zizanioides*, used in our study, is a plant with a massive root system that could have enhanced the treatment efficiency for organic matter.

### 3.5. Nutrients Removal Performance

If the desired reuse option of the treated greywater is for irrigation, it makes less sense to remove nutrients (nitrogen and phosphorus) as suggested by von Sperling and Platzer [40] and Oakley [52]. Nevertheless, we are evaluating the treatment efficiency of nutrients to know the real performance of our treatment system operated in the Sahelian climatic conditions. As shown in Figure 5, the treatment efficiency of all nutrients is greater than 60% with remaining concentrations of 9.46, 158.00, 6.91 mg/L for nitrate, ammonium, and orthophosphate, respectively, measured in the treated effluent.

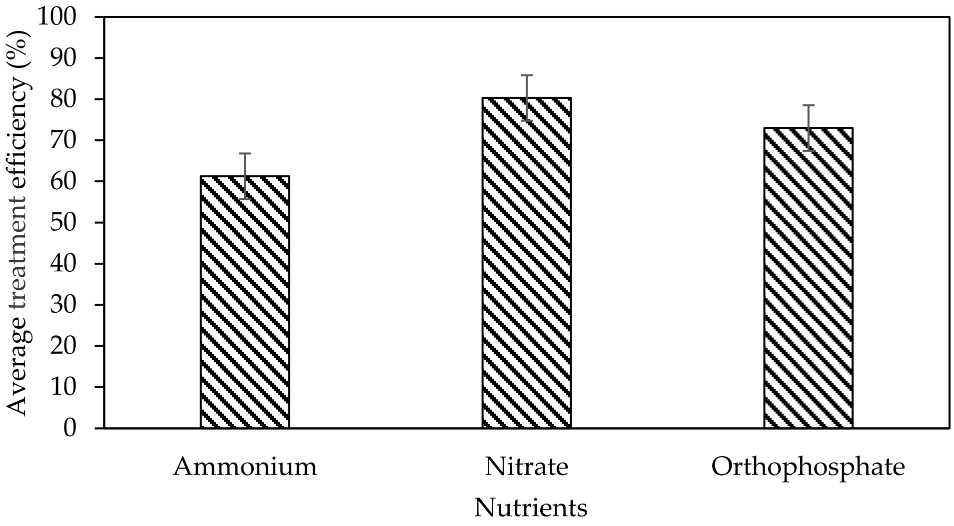


**Figure 5.** Average treatment efficiencies for nutrients for the entire greywater treatment system.

In CWs, nitrogen is transformed or removed through several mechanisms including mineralization, volatilization, nitrification, denitrification, plant and microbial uptake, etc., of which nitrification seems to be the most important pathway followed by denitrification [53]. While vertical flow CWs successfully remove ammonium through nitrification, horizontal flow CWs are less effective at nitrifying ammonium and more favorable to denitrification [47]. This finding could explain the treatment efficiency of nitrate (80%) being higher than that of ammonium (60%) in our study (Figure 5). The high potential for nitrate reduction in horizontal flow CWs is due to the presence of anaerobic conditions [47]. Additionally, the optimum pH for significant nitrification ranges from 6 to 8 [47]. The pH values of the greywater for the entire treatment system, which ranged from 7.16 to 8.71, probably promoted this process. However, ammonia volatilization, which is controlled by pH, was likely not a significant process in our treatment system, with the pH values obtained being lower than 10, the lowest value required for significant volatilization to occur [53].

The treatment efficiency of orthophosphate for the whole treatment system is 73% (Figure 5). Three main mechanisms contribute to phosphorus removal in CWs: plant uptake, microbial immobilization, and filtration media through phosphorus sorption and complexation. The treatment efficiency of phosphorus is generally lower than that of nitrogen, due to the low efficiency of the three mechanisms involved [47].

Nitrogen and phosphorus are ranked as the two most important factors to enhance soil fertility in Sub-Saharan Africa. Unfortunately, the lack of access to financial resources to purchase fertilizers is a major barrier for improving soil conditions there [54]. Assuming 104 L of greywater are generated per day by a household of eight with effluent characteristics provided in Table 1, one household system could potentially produce 4745 g of nitrogen and 50 g of phosphorus annually. Because nitrogen fertilizer is very important for food self-sufficiency in Africa [55], our study shows treated greywater can be a source of this important nutrient. This is because nitrogen input in agriculture is very low in most African countries where annual usage is, on average, less than 7000 g of nutrients per ha [55]. In fact, if the treated greywater is used to produce vegetables that are known to alleviate nutrient deficiency [56], our calculations indicate treated greywater can provide the required nitrogen for the top five year-round consumed vegetables in Burkina Faso (tomatoes, onions, carrots, lettuce, and cucumber) if grown in a small household garden [57,58].

### *3.6. Analysis of the Performance of the Treatment System*

The analysis of the data obtained from the raw, pre-treated, and treated greywater show significant positive correlations between the SS content of the pre-treated greywater and the treatment efficiency of the planted section ($R^2 = 0.705$, $p < 0.01$) and the SS content of the raw greywater and the overall performance of the treatment system ($R^2 = 0.665$, $p < 0.05$) (Figure 6). Significantly positive linear correlations are also observed between fecal coliform content in the raw greywater and their overall removal efficiency ($R^2 = 0.666$, $p < 0.05$) and for the enterococci content in the raw greywater and their overall removal efficiency ($R^2 = 0.550$, $p < 0.05$). The positive correlations from this set of data suggest that the characteristics of the influent greywater (i.e., pollutant concentration) have an important impact on the performance of the treatment system. From a recent review study involving several constructed wetlands, Wu et al. [49] observed positive significant linear correlations between COD loading rate and COD removal rate, $NH_4^+$-N loading rate and $NH_4^+$-N removal rate. They found the correlations between pollutant loading and removal rates to be logical because a higher loading rate should provide a greater mass of pollutants that leads to higher treatment efficiency in certain unit processes that employ sedimentation and adsorption.

Based on the correlation analysis, SS and enterococci were selected to show the evolution of the performance of the different sections of the treatment system over time (Figure 7). For SS, the overall performance of the greywater treatment system is high, with low fluctuation in TE over time. The fluctuation is much larger in the pre-treatment phase compared to the treatment stage (planted section). This observation could be explained by the difference in the particle size of the materials used in each step. Overall, for the planted section, the performance seems high at the beginning and declines from the sixth week (10th week of operation), while that of the pre-treatment stage stabilizes at slightly higher values. These findings could be linked to the progressive filling of voids by particulate matter (faster in the case of sand and longer in the case of granite).

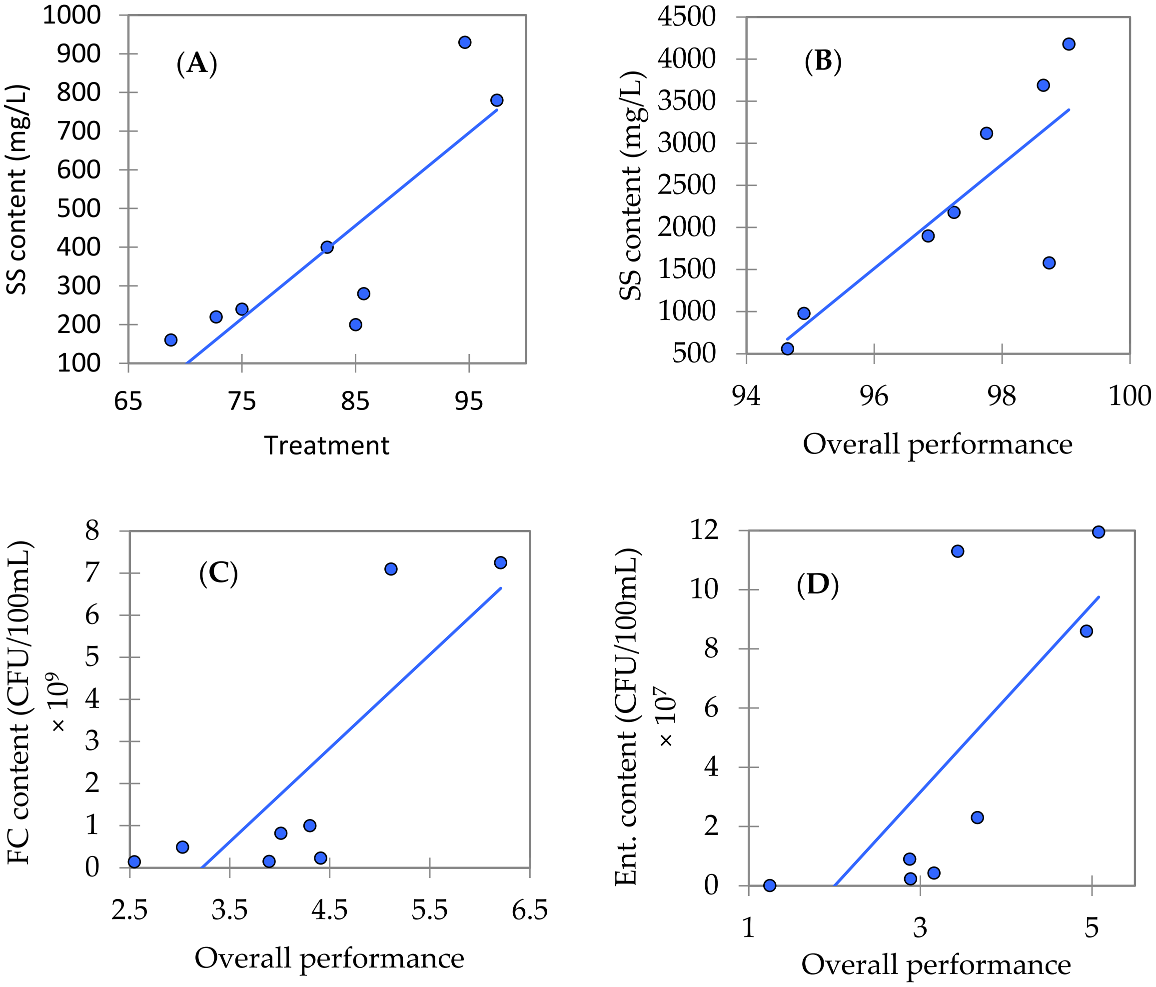
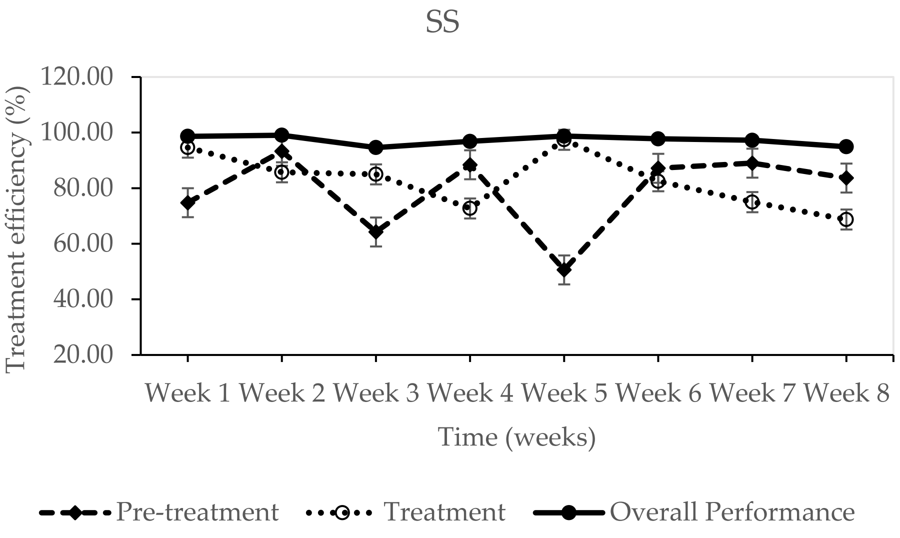


**Figure 6.** Correlation analysis between influent quality parameters (SS, fecal coliforms, and enterococci) and the removal efficiency of the treatment system. (**A**) Correlation between SS content of the pre-treated greywater and the treatment efficiency of the planted section ($R^2 = 0.705$, $p < 0.01$); (**B**) correlation between SS content of the raw greywater and the overall performance of the treatment system ($R^2 = 0.665$, $p < 0.05$); (**C**) correlation between fecal coliforms content of the raw greywater and the overall removal efficiency of fecal coliforms ($R^2 = 0.666$, $p < 0.05$); and (**D**) correlation between enterococci content of the raw greywater and the overall removal efficiency of enterococci ($R^2 = 0.550$, $p < 0.05$); SS: suspended solids; FC: fecal coliforms; Ent. = Enterococci.

For enterococci, there is an overall trend towards an increase in the performance of the greywater treatment system over time. However, for both the pre-treatment and treatment stages, there is a large fluctuation in the performance values. This fluctuation is due to the fact that the performance of the filters is affected by several factors including the pollutant loading at the entrance to the treatment system, the particle size, the quantity of particulate material retained by the filter, and hydraulic and environmental conditions [19,49].

However, this comparison of the contribution of each treatment phase depends on several parameters, the most important of which is the difference in the characteristics of the greywater influent. As pre-treated greywater becomes the influent in the treatment phase, the pollutant loading decreases making constituents of concern more difficult to treat.



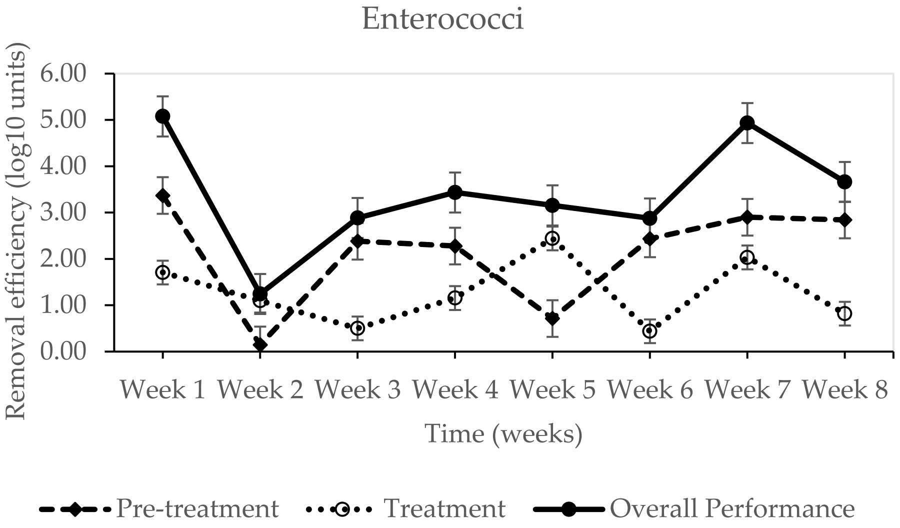


**Figure 7.** Performance of the different sections of the greywater treatment system over time. Pre-treatment: from sampling location 1 to location 2; Treatment: from sampling location 2 to location 3; Overall Performance: from sampling location 1 to location 3.

### *3.7. Limitations of the Treatment System*

Despite its promising performances, the treatment system has some limitations:

- The lack of a greywater collection network in rural households and the need for an appropriate system that does not utilize mechanical energy complicates the collection of greywater. The available alternative employed here was the manual collection and the gravitational flow of the greywater that requires raising the level of the shower room; this elevation may be detrimental to some elderly occupants. However, we have included a staircase system for easy access to the shower room;
- The influent is a mixture of three different greywater sources produced randomly in the household; this complicates the possibility of obtaining homogenous greywater influent for the performance evaluation. In future monitoring, the small water collection device we used to collect the influent could be replaced by a small settling tank;
- The use of filter materials with a reduced particle size to increase the purification performance may result in a reduction in the operating time before clogging, which may require frequent maintenance. Nevertheless, after 7 months of operation, the system was functioning normally, probably due to the presence of plants, which,

through their roots, can help reduce clogging. Training household members to limit the input of excessive external sand is recommended to reduce the possibility of clogging;

- Despite the observed microbial removal efficiency of greater than 3 log10 units that meets World Health Organization Guidelines for restricted irrigation, the residual concentrations remain close to the set guidelines. Therefore, further research should be carried out to improve the microbial removal performance. A sunlight-based disinfection section can be proposed (by integrating an open basin before the storage tank). However, open basins may promote mosquito breeding. Therefore, this section should be designed in such a way as to prevent mosquito breeding;
- Many studies have shown the treatment efficiency of planted horizontal flow CWs is greater than in unplanted systems [35,59]. Plants are known to uptake nutrients and help to remove organics. Planted systems, even as incorporated into subsurface CWs, are also expected to exhibit enhanced removal of microorganisms because plants support removal mechanisms such as filtration and adsorption [16]. However, there have been conflicting reports regarding the expected benefits of planted systems in terms of improving water quality [59]. Furthermore, recent reviews of the performance of planted bioretention systems that manage stormwater (a form of subsurface treatment operated in a vertical hydraulic orientation) conclude that though vegetation in bioretention systems is expected to result in measurable water quality and hydrologic performance benefits [60], studies on planted bioretention systems do report contradictory results for pathogen and nutrient removal [61,62]. One possible reason for this conflicting result in a bioretention system is because planted systems may increase permeability which then decreases retention time and hence results in decreased pathogen removal [61]. In either case, plant processes in CWs still need to be further researched and developed to improve greywater systems.

## 4. Conclusions

This study implemented and assessed a full-scale constructed wetland designed to collect and treat shower, dishwashing, and laundry greywater generated by a rural household located in Africa's Sahel region. Results showed the overall removal of organic matter was greater than 90% and orthophosphate and ammonium were reduced by 73% and 60%. Reusing some of the embedded nutrients in our greywater treatment system shows the potential to create synergy between sanitation and food security development goals [63]. The removal efficiency of fecal bacteria varied from 3.41 (enterococci) to 4.19 (fecal coliforms) log10 units which meets World Health Organization Guidelines for restricted irrigation (but remained close to guideline values). Based on these findings, the developed technology can be considered as a promising option for greywater management in arid regions found in the developing world such as experienced in the Sahel region of Sub-Saharan Africa. Despite some limitations, the developed technology can be considered for household greywater treatment for agricultural reuse in arid regions of developing countries that experience water scarcity, climate variability, and land degradation. This is especially important because, even though produced greywater is recognized as an underutilized resource in many parts of the world, studies such as this can help to encourage adoption of safe greywater reuse in areas that enhance food security.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16131927/s1, More details on the design of the treatment system can be found in this Supplementary Material File.

**Author Contributions:** Conceptualization, Y.M.; methodology, Y.M., C.O.T.C., M.S. and I.N.; validation, Y.M. and A.S.O.; formal analysis, Y.M. and C.O.T.C.; investigation, Y.M., C.O.T.C., M.S. and I.N.; data curation, Y.M., C.O.T.C., M.S. and I.N.; writing—original draft preparation, Y.M.; writing—review and editing, Y.M., A.S.O., J.R.M., S.K.S., H.Y. and M.D./K.; visualization, Y.M., C.O.T.C. and J.R.M.; supervision, A.S.O. and J.R.M.; project administration, Y.M., M.D./K., H.Y. and S.K.S.; funding acquisition, Y.M., M.D./K., S.K.S., H.Y. and J.R.M. All authors have read and agreed to the published version of the manuscript.

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