Novel Design Concept for Facultative Ponds Using Rock Filters to Reclaim the Effluent

Rashed Al-Sa`ed[1]; Maher Abu-Madi[2]; and Omar Zimmo[3]

Abstract: This paper presents a novel design concept for using rock filters as in-line natural media in waste stabilization ponds. A pilot-scale algae-rock-filter pond (ARP) system was investigated in parallel with algae-based ponds (ABPs) over a period of 6 months to evaluate the treatment efficacy of both systems. Each system entailed four equally sized ponds in a series and was continuously fed with domestic wastewater from Birzeit University. The removal rates of organic matter, nutrients, and fecal coliforms were monitored within each treatment system. The results obtained revealed that the ARP system was more efficient in the removal of organic matter [total suspended solids (TSS) and chemical oxygen demand (COD), 86% and 84%, respectively] and fecal coliforms (4 log) than the ABP system (81%, 81%, 3 log, respectively). The ARPs showed higher removal rates for ammonium and phosphorus (68.8% and 50.0%, respectively) compared with the ABPs (57.9% and 41.5%, respectively). The biogenic-aerated ARP option is a cost-effective and land-saving alternative with effluent quality suitable for restricted agricultural irrigation. The ARPs utilizing a new algae-biofilm design concept should be investigated at a large scale to enhance the information available to relevant decision makers, who are seeking sustainable on-site wastewater treatment alternatives.
DOI: **10.1061/(ASCE)EE.1943-7870.0000318.**

CE Database subject headings: Domestic wastes; Filters; Nitrification; Abatement and removal; Water reclamation; Biofilm; Waste stabilization ponds; Wastewater management.

Author keywords: Domestic wastewater; Algae-rock filter; Effluent reclamation; Nitrification; Algae-biofilm; Removal efficacy; Waste stabilization ponds; On-site wastewater treatment.

Introduction

The prevailing arid and semiarid conditions in Palestine make the reuse of treated and reclaimed effluents for agricultural and industrial purposes imperative to increase and secure economical development and achieve environmental protection. The widening gap between water supply and demand can be reduced effectively with reclaimed domestic and municipal wastewaters. Approximately 17% of the total domestic and municipal wastewater collected in central sewer networks experience treatment in on-site and central wastewater treatment plants (WWTPs). However, both the on-site and central sewage works are not operated adequately nor are they maintained properly, making treated effluent unsuitable for unrestricted agricultural irrigation. Because of limited access to freshwater sources, farmers eagerly use both raw and partially treated wastewater for agricultural irrigation (Al-Sa`ed 2007).

The current on-site wastewater treatment systems in Palestinian rural communities were sited and designed based on site-specific conditions and funding agency guidelines with little attention paid to the surrounding environment (soil, surface, and groundwater) or the potential of cumulative effects resulting from decentralized wastewater treatment systems. The numerous cases of poor treatment performance of on-site systems reported recently highlight the need for the upgrading of mismanaged, overloaded, and nonfunctional on-site treatment systems underpinned by solid and reliable scientific knowledge gained from technically and economically feasible process retrofitting approaches (Al-Sa`ed 2007).

Conventional waste-stabilization ponds, called algae-based ponds (ABPs) in this paper, are considered as a low-cost and appropriate wastewater treatment technique worldwide (Tchobanoglous and Angelakis 1996; Mara and Pearson 1998; Tsagarakis et al. 2000; Archer and Mara 2003; Al-Sa`ed and Mubarak 2006). However, major limitations include high effluent concentrations in total suspended solids (TSS) and nitrogen because of large quantities of algal cells and deficiency in nitrification, respectively. The presence of TSS and nitrogen-rich effluent can restrict effluent reuse in agricultural irrigation, pose public health risks, and degrade water quality of receiving water bodies. Nitrogen compounds removal in ABPs is governed by nitrification and denitrification (Mara 2000; Zimmo et al. 2004; Camargo Valero and Mara 2007), whereas others (van der Steen et al. 1998; El-Shafai et al. 2007) reported that nitrogen removal consisted of 80% by plant uptake in duckweed-based ponds (DBPs).

Improving the ABPs performance for the removal of organics, nitrogen, and heavy metal pollutants through the addition of artificial fibrous carriers (attached growth media) in the pond water with different configurations was reported by a few pilot-scale studies (Swanson and Williamson 1980; Shin and Polprasert 1988; Polprasert and Charnpratheep 1989; Qi et al. 1993; Smith 1993; Saidam et al. 1995; Middlebrooks 1995; Zhao and Wang 1996). Recently, laboratory and field research done by Shilton et al. (2005) using packed column biofilters in ABPs revealed that limestone and iron slag when used as media were effective in

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Note. This manuscript was submitted on June 2, 2008; approved on August 27, 2010; published online on September 1, 2010. Discussion period open until September 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Environmental Engineering***, Vol. 137, No. 4, April 1, 2011. ©ASCE, ISSN 0733-9372/2011/4-284–290/$25.00.

phosphorus removal. Also, the erection of aerated rock filters (Johnson and Mara 2005) were also investigated; however, they were associated with increased capital and annual running costs (Tsagarakis et al. 2000; Archer and Mara 2003; Barjenbruch and Erler 2005). Without adequate design concepts, Al-Sa`ed (2007) verified the large areal demand of both ABPs and DBPs (3–7 $m^2/capita$) to achieve acceptable nutrient removal rates under Mediterranean conditions (van der Steen et al. 1998; Zimmo et al. 2005), thus rendering the potential of wide application as low-cost options for rural and periurban areas in the developing countries.

In Germany, the layout and design of ABPs (ATV-DVWK Arbeitsblatt A 201 2004) is made according to the daily surface chemical oxygen demand (COD) load and they require a large specific land area between eight and 10 $m^2/capita$. In Palestine, limited data are available pertinent to design, operation, nutrient, and pathogen removal rates of on-site treatment systems. However, annual monitoring reports of the Palestinian Water Authority (PWA) on nitrates and pathogens in groundwater and surface water revealed water quality deterioration (PWA, personal communication, 2007). The aim of this study was to develop a new design concept and investigate its effectiveness by using rock filters as in-line biofilm media in the facultative ponds [algae-rock-filter ponds (ARPs)] to remove organic matter, nutrients, and pathogens from domestic wastewater in a pilot-scale system. ABPs were used as a control. Because of variable volumetric and hydraulic loads as design parameters, the treatment efficacy of both systems was evaluated, arguing that the algae-bacteria symbiosis of ARPs performs better than conventional ABPs. Modeling of process kinetics as to nitrogen and pathogens removals is beyond the scope of this research. Depending on the planned effluent use, the guidelines recently adopted by the World Health Organization (WHO) (2006) and the current valid Palestinian Standards Institution (2003) were used as a basis for the suitability of effluent reuse for agricultural purposes.

Materials and Methods

Description of the Pilot Plant

Both pilot-scale systems, ABPs and ARPs, are installed adjacent to the central WWTP at Birzeit University campus. Similar to ABPs, the ARPs consisted of four subsequent ponds—one anaerobic, two facultative, and one polishing pond—built in concrete with the dimensions of 3.0 × 1.0 × 1.0 m each, including rock-filter media installed within. The rock biofilters were immersed in the two facultative ponds (ARP1 and ARP2) to establish the algae-biofilm media by using natural media (locally named as Kharrami stones), where the stones were stocked in low-cost plastic boxes (eight boxes each). The rock-filter media is locally available at a low cost and is stable with a specific surface area of approximately 90 m^2/m^3. Two vertical layers of four plastic boxes, containing the rock filters were overlaid above one another and were installed in each side of the two facultative ponds with three wooden vertical baffles that prevent short-circuiting and improve the overall mixing pattern.

Fig. 2. Overview of the upgraded systems (wooden baffles and biofilter in ARPs) (photos courtesy of Maher Abu-Madi and Omar Zimmo)

The ABP system used in this study has the same layout of the modified one but without having rock filters. Three wooden vertical baffles were also installed in co-counterflow mode, which prevents short-circuiting and improve the overall mixing pattern. A schematic flow diagram of the two pilot-scale plants (ABPs and ARPs) is shown in Fig. 1.

Fig. 2 illustrates an overview of the pilot-scale treatment systems under study after upgrading the existing one with fixed film media and making geometric modifications on the inlets and outlets as well as the installment of a passive aerator (U-shaped plastic pipes with small perforations) and vertical wooden baffles.

Experimental Design and Analytical Methods

Both pilot-scale treatment systems were fed with an influent of domestic origin produced at Birzeit University campus, pumped directly from the balancing tank, a preliminary treatment unit with intermittent aeration of the central biological treatment system. The volumetric loads applied were gradually increased over time by increasing the volume of wastewater flowing into the treatment systems. Two facultative ponds (ARPs) were seeded with activated sludge taken from the mechanized WWTP to initiate the biofilm

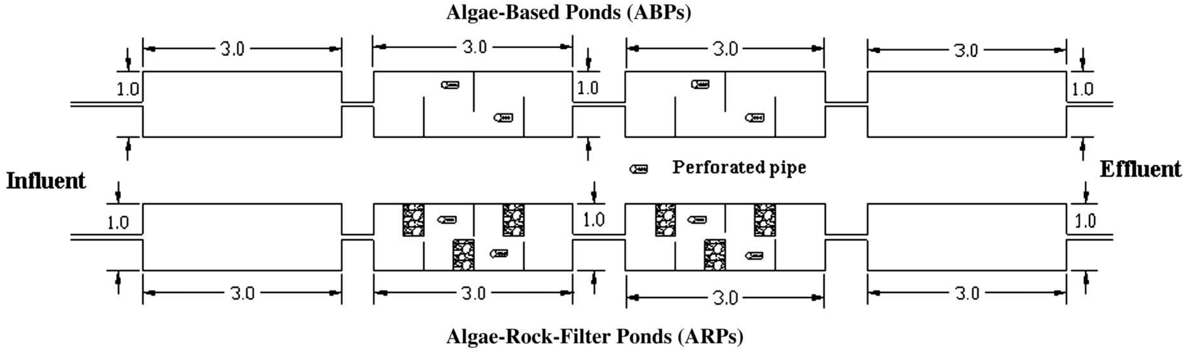


Fig. 1. Schematic flow diagram of the pilot-scale pond systems (dimensions are in meters)

growth on the rock filters. The inlet pipe was inserted in an inverted L-shaped tube placed at the left corner of the anaerobic pond to ensure equal distribution of the influent and to minimize short-circuiting.

Both treatment systems were continuously fed by using a pump installed in the balancing tank at a constant flow rate of 1 m^3/day to a constant level tank, from which each treatment system received a daily flow of 0.5 m^3 through a variable speed, two-head, heavy duty, peristaltic pump. After the start-up phase, two other experimental phases were performed by applying variable daily hydraulic loading rates (Phase 1 and 2 with 0.7 m^3 and 1.0 m^3, respectively). The wastewater flow to the remaining ponds was by gravity, whereas the effluent of polishing ponds from both treatment systems was discharged into the slow sand filter well of the mechanized treatment plant. Table 1 summarizes the operational design parameters during the start-up phase for the both treatment systems.

Both systems were monitored during the start-up phase between December 2005 and February 2006 when the hydraulic retention time (HRT) was approximately 22 days ($Q = 0.5$ m^3/day), and from March to August 2006 during the second ($Q = 0.7$ m^3/day) and third ($Q = 1.0$ m^3/day) run phases, in which HRTs between 15 and 11 days prevailed, respectively. Grab samples from the inlet and outlet of each pond series were taken regularly (HRT-based) during the various experimental phases. Following the analytical procedures directed by the *Standard Methods for the Examination of Water and Wastewater* (APHA et al. 1998), all samples were assessed for their content using the following methods: 5220 C for COD, 2540 D for TSS, 4500-NH3D for dissolved forms of nitrogen, and 9222 D for fecal coliform (FC) bacteria. Dissolved oxygen (DO), hydrogen ion concentration (pH), and temperature were measured on site by using a YSI Inc. 610-DM probe. Several other physicochemical and operational parameters corresponding to the operation phases were also measured and are summarized in Table 2. Owing to budget limitations, the limited sampling program chosen allowed neither for an additional parameters analysis nor for a detailed statistical analysis.

Results and Discussion

Operation and Performance Evaluation

During the first experimental run (start-up phase), both systems reached a steady-state process, in which grab samples of the final effluent from the ABPs and ARPs revealed an average COD value of 140 and 75 mg/L, respectively. However, because of low temperature (12ºC) during the cold winter season (January–February 2006), the start-up phase took almost one month for the ARPs to establish a healthy biofilm. This was confirmed through microscopic trials [Figs. 3(a) and 3(b)] made by using a phase contrast microscope by well-established symbiosis of algae, protozoa, and bacterial flocs on the rock-filter media. Fig. 3 clearly illustrates our argument that algal biomass made the biogenic oxygen available for the newly established microbial communities on the rock filters.

During the start-up phase, the mean values for all parameters measured in the grab samples of influent and pond effluents in both experiments are presented in Table 2. Despite wide fluctuations in the influent, both treatment systems reached steady-state conditions as to effluent quality. The mean pond influent temperatures averaged 16.8°C throughout the start-up phase, 23.5°C in the second experimental period, and 27.8°C in the third. In both periods, the pH decreased slightly from the raw sewage to the anaerobic pond effluent and then gradually increased along the series, reaching mean values in the final effluent of 7.86 and 7.97 in the effluent of ARPs and ABPs system, respectively. In ARPs, the DO concentration was 1.88 mg/L in the readings taken from 0.15 m below pond surface and 1.66 mg/L in the effluent from the ABPs control. The higher values in the ARPs effluent might be attributed to higher biogenic DO production through the algae-bacteria symbiosis.

Table 1. Operation Design Criteria for the Start-Up Phase in Both ABPs and ARPs

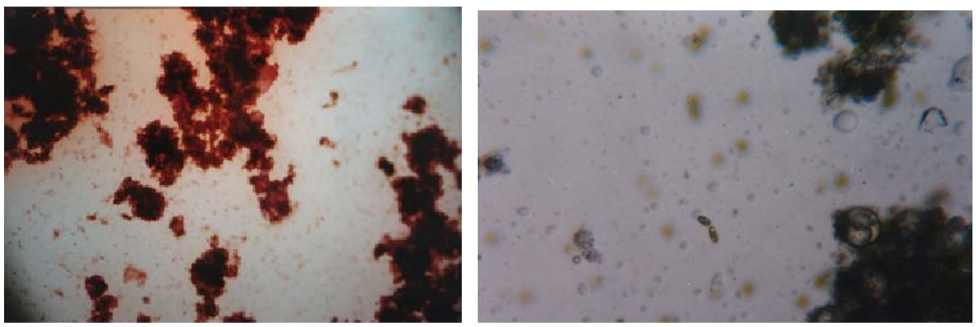
	Number of units	Width (m)	Length (m)	Depth (m)	Water depth (m)
Algae-based pond (ABP) 1	4	1	3	1	0.9
Algae-rock-filter ponds (ARP1 and ARP2)	4	1	3	1	0.9
Applied organic surface loading rate					
Optimal design rate	168	kg COD/(ha · d)		Optimal design	
Organic loading rate	16.8	g COD/(m^2 · d)		< 20 g COD/(m^2 · d)	
Daily flow rate Q (each lain)	0.5	m^3/d		Start-up phase	
Influent concentration C_i COD	775	mg/L			
Daily COD organic loading rate	0.39	kg COD/d			
Operational design criteria for ABPs and ARPs					
ABPs	AnP1	ABP1	ABP2	PP1	Total
ABP surface area (m^2)	3	3	3	3	12
ABP volume (m^3)	2.7	2.7	2.7	2.7	10.8
Organic loading rate (g COD/m^2 · d)	129	30	15	7.5	
HRT (d)	5.4	5.4	5.4	5.4	21.6
ARPs	AnP1	ARP1	ARP2	PP1	Total
ARP surface area (m^2)	3	17.4	17.4	3	40.8
ARP volume (m^2)	2.7	2.86	2.86	2.7	11.12
Organic loading rate (g COD/m^2 · d)	129	5.2	2.6	1.3	
HRT (d)	5.4	5.72	5.72	5.4	22.24

Note: AnP = anaerobic pond; PP = polishing pond.

Table 2. Characteristics of the Influent Feeding the Pilot-Scale Treatment Plants

Parameter[a]	Sampling date							Average	SD ±
	1/03/06	15/03/06	03/04/06	04/05/06	23/05/06	07/08/06	23/08/06		
T°C (water)	21	15	19.5	23.0	24.5	28.0	27.5	22.6	4.6
pH (-)	7.95	7.75	8.05	7.84	8.01	7.75	7.62	7.9	0.16
DO (mg/L)	2.6	3.5	3.21	1.52	3.6	2.0	2.5	2.7	0.78
EC (μs/cm)	1,423	1,448	1,598	1,006	1,340	1,365	1,640	1,403	208
TSS (mg/L)	149	207	230	346	323	386	525	309	127
COD (mg/L)	673	560	883	613	750	557	579	659	121
NH_4-N (mg/L)	75	65.4	88.3	70	91.6	64.5	81.1	76.6	10.8
PO_4-P (mg/L)	8.2	8.0	12.5	7.8	6.4	11	8.8	9.0	2.1
FC[b]	4.9×10^8	1.75×10^8	4.9×10^8	1.35×10^8	1.38×10^8	2.84×10^8	3.65×10^8	2.97×10^8	1.65×10^8

[a]Number of grab samples: 7 (duplicate analysis).
[b]FC = fecal coliforms; unit as colony-forming units per 100 mL.



(a) (b)

Fig. 3. (a) Microscopic picture of a biofilm from ARP system (Gram stain picture; x 1,000); (b) compact algal-biofilm biozenosa (free swimming bacteria, protozoa, and algae; x 1,000) (photos courtesy of Rashed Al-Sa `ed)

The ABPs' effluent contained less DO than the facultative pond effluent of the ARPs throughout all run phases.

During the second experimental run (HRT 11 days), COD and TSS removals were much higher in the passive aerated algae-rock filter than in the ABPs. The mean COD and TSS removals were 87.5% and 87.3%, respectively, in the ARPs, compared with 81.7% and 78.6% in the ABP controls (Figs. 4 and 5). The average effluent COD concentrations were 85 mg/L in the passive aerated filter and 125 mg/L in the ABP controls; the corresponding figures for the TSS were 42 and 71 mg/L. The effluent TSS content in both systems is predominantly of algal origin, because the majority of the nonalgal solids were removed in the facultative ponds. The effluents from both systems, therefore, comply with the effluent requirements of ≤ 20 mg/L biological oxygen demand (BOD) and ≤ 50 mg/L TSS commonly set for small wastewater treatment works with medium effluent quality (class C) by the Palestinian Standards Institution (PSI 2003).

The results of our initial work during the first-run phase (March–April 2006) on both treatment systems revealed that the daily hydraulic loading rate (HLR) of 0.19 m^3/m^3 had shown no major differences on the facultative pond effluents of both ABPs and ARPs. Both systems maintained a stable effluent quality at an increased daily HLR of 0.26 m^3/m^3 at the beginning of May 2006. Johnson and Mara (2005) reported that BOD and TSS removals were much higher in the aerated filter than in the unaerated filter, in which the 95-percentile effluent COD concentrations

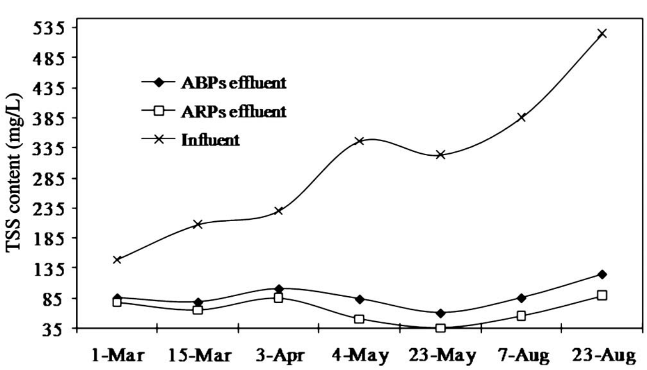


Fig. 4. Influent TSS, ABP, and ARP effluent quality during the three run phases

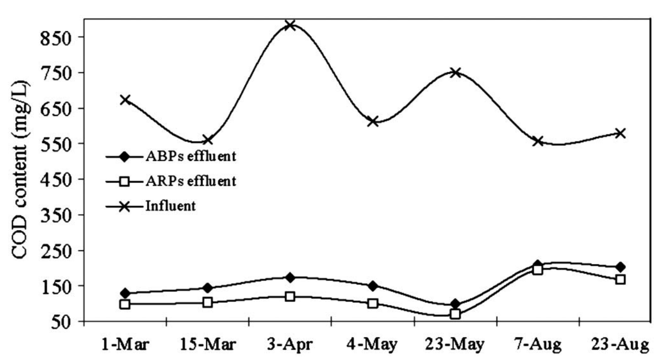


Fig. 5. Influent COD, ABP, and ARP effluent quality during the three run phases

were 54 mg/L in the aerated filter and 190 mg/L in the unaerated control, and the corresponding figures for TSS were 25 and 60 mg/L, respectively. These data confirmed the early results reported by Saidam et al. (1995) on upgrading ABPs effluent by using a pilot-scale rock-filter pond (unaerated) after the polishing ponds at As-Samra waste stabilization ponds, where effluent TSS was around 100 mg/L. The limiting factor was the HLR (0.27–0.5 $m^3/m^3 \cdot d$) applied by Saidam et al. (1995), whereas Johnson and Mara (2005) found that 0.15–0.3 $m^3/m^3 \cdot d$ was the optimal range for achieving effluent quality requirements commonly set for small WWTPs by the Environment Agency of England and Wales.

According to the experimental data obtained during the third-run phase (Fig. 5), doubling the HLR (from 0.20 to 0.40 $m^3/m^3 \cdot d$) has reduced the COD removal efficacy in the ABPs (64%) much more than the ARPs (73%). This might be because of the lower surface organic loading rate (OLR) exerted by the rock filter installed in the facultative ponds. The results indicate that ARPs can tolerate higher surface organic loading rates (i.e., HLRs) and they produced a COD effluent of 150 mg/L compared with 208 mg/L for the ABPs. The TSS removal in both systems showed similar tendencies at higher HLR. To this end, ABPs can achieve a similar effluent quality to the ARPs, only when there is an additional installment of land area, implying extra financial investment compared to land-saving ARPs. Irrespective of the population served by the individual pilot-scale systems, the total surface area available within the ARPs was 41 m^2 compared to ABPs with only 12 m^2, leading to a factor of 3.4-fold in capital investment for land area when considering the conventional ABPs without rock-filter media. This can be best illustrated by taking operational conditions during the second-run phase, in which each of the systems served approximately four capita. The difference in COD surface loading rates applied during this run phase on ARPs and ABPs was 12 and 40 g $COD/m^2 \cdot d\vartheta$, respectively, implying a ratio of 3.4 for ABPs to achieve the same effluent quality produced by the ARPs.

Making a minimal statistical analysis (geometric means and standard deviations) of the results obtained revealed variations in the overall performance of both treatment systems during the whole period of this study. Table 3 summarizes the overall treatment efficacy of TSS, COD, NH_4-N, and PO_4-P under variable HLRs and OLRs. Over a 6-month period, ARPs with oxygen source from algal photosynthesis and passive aeration, using installed vertical perforated pipes, provided favorable conditions within the rock filter for nitrification process to occur.

The results listed in Table 3 show that the geometric mean of NH_4-N and PO_4-P concentrations in the effluent from the ARPs were 23.9 mg N/L and 4.5 mg P/L, respectively, whereas the ammonium and phosphate concentrations in the effluent from the ABPs were 32.2 mg N/L and 5.3 PO_4-P/L, respectively. A slightly higher nitrification rate of 68.8% was found in the ARPs, compared to 57.9% in ABPs. This is a result of the surface area provided by the rock filters installed within the facultative ponds (ARPs), enhanced proliferation of bacterial biomass (biofilm), and the availability of the biogenic oxygen source produced by the algae (Shin and Polprasert 1988; Mara and Johnson 2006). The installed vertical baffles in both systems might have also induced a plug-flow pattern, which reduced short-circuiting and aided in contact between substrate and biofilm on the rock filters (Juanico 1991; Middlebrooks 1995; Zhao and Wang 1996). To explain the real mechanisms of biofilm formation/decay or to predict a model for hydraulics impact on the efficacy of waste stabilization ponds are beyond the scope of this study and need further investigation.

Table 3. Process Performance Summary for the ABP and ARP Treatment Systems

Parameter[a]/system	$TSS_{effluent}$		$COD_{effluent}$		NH_4-$N_{effluent}$		PO_4-$P_{effluent}$	
	ABPs	ARPs	ABPs	ARPs	ABPs	ARPs	ABPs	ARPs
Average (mg/L)	84.4	70.1	158	128	32.2	23.9	5.3	4.5
Efficacy (%)	72.7	77.3	76	80.5	57.9	68.8	41.4	50.0
Minimum (mg/L)	42	38	129	70	30.6	18.5	4.1	3.3
Maximum (mg/L)	124	89	144	103	34.8	27.6	6.3	5.2
SD (±)	25.1	19.2	39.4	43.7	2.0	3.1	0.84	0.65

[a]Number of grab samples: 7 (duplicate analysis).

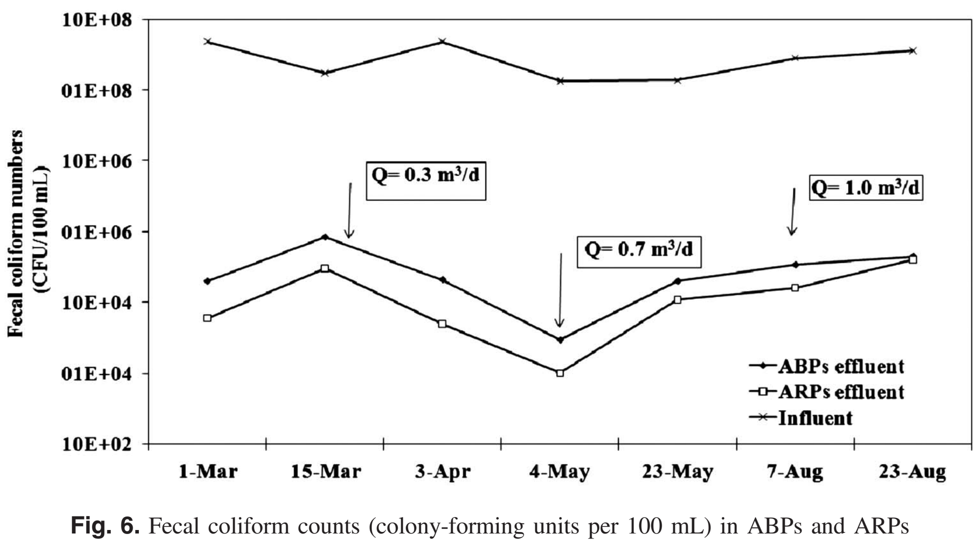


Fig. 6. Fecal coliform counts (colony-forming units per 100 mL) in ABPs and ARPs

The ABPs produced an effluent that complied with the Palestinian effluent quality standards of 200 mg COD/L and 50 mg SS/L (class D = bad quality), but the effluent from the ARPs was able to comply with class C (medium effluent quality) requirements of less than 150 mg COD/L and 35 mg N/L, both for discharge into surface water bodies. Both systems complied with sets of effluent quality requirements commonly set for small on-site wastewater treatment systems by the Palestinian Standards Institution (PSI 2001). Depending on the type of irrigation systems to be used for effluent reuse in agricultural irrigation, the treated effluent of both treatment systems shall be reclaimed by installing other rock filters within the outlet of the polishing ponds; this will reduce the TSS content in the treated effluent.

Average concentrations for FCs as indicator bacteria are presented in Fig. 6 for the ABPs and ARPs treatment systems. By using the influent to the anaerobic ponds as the starting point, individual system component percentage removals were calculated to determine the cumulative removal by each system. During the second run phase, the ARP systems showed an overall removal of 99.96% of FCs compared with 99.89% for the ABPs. During the second-run phase, ARPs showed higher removal rates (77%) in FC content between the inflow of facultative ponds and the polishing ponds effluent, whereas the cumulative system reduction for FC was only 69.1% in the ARP systems during the same run phase. Previous studies (El-Hamouri et al. 1996; Rangeby et al. 1996; USEPA 2002) indicated that the FC removal may be attributed primarily to removal in the anaerobic ponds as a result of cell die-off and settling of the materials, degradation of organic matter, and competition of microorganisms for the limited nutrients or trace elements, and cell wall desiccation. In the ARP systems, filtration, adsorption, aggregate formation, and predators attributed to passive aerobic conditions and rock-filter-media surface area may favor the higher FC removal rates observed (Mara and Johnson 2006; Johnson et al. 2007).

Because of the FCs, the Palestinian guidelines (PSI 2003) set three quality categories on effluent disposal and reuse; Category A for high quality (< 200 CFU/100 mL) and B to D for good (< 1,000 CFU/100 mL) to bad effluent quality. Despite improvement in ABPs hydraulics through baffles and rock filters, the results shown in Fig. 6 indicate that the treated effluent from both treatment systems did not comply with the PSI effluent requirements for unrestricted irrigation. However, depending on the ultimate effluent reuse purpose, enhanced pathogens removals were achieved by installing chlorinating units, reed beds, and rock filters at the polishing pond exits (Jagals and Lues 1996; Government of Jordan 2003; Mara and Johnson 2007; Camargo Valero and Mara 2007).

Conclusions

The results of these investigations show the possibility of effluent reclamation with the aid of a new design concept by using in-line rock filters in the facultative ponds (ARPs) to develop an algae-bacteria biofilm system. ARPs are innovative solutions that revealed higher treatment efficiency than conventional waste stabilization ponds. The new design concept has promoted algal-bacterial symbiosis and better-tolerated higher volumetric organic loads, and, thus, reduced the capital investment for land requirements by a magnitude of 3.3-fold. Furthermore, the developed system has many benefits because of construction, installment, and operation. This preliminary study is to be extended into a more comprehensive research program aiming at assessment and monitoring of algae-bacterial biofilm on rock filters in ABPs. In particular, we will work toward better understanding and process modeling in relation to the removal of nitrogen compounds and other pathogen species by using rock filters in large-scale facultative ponds. Although some progress has been made in understanding the processes that govern the algal-biofilm layer, there is still a lot to be learned before adequate process design and control models can be developed. Finally, whether the improved hydraulics in the ARPs are behind the enhanced FC removal needs to be further investigated in more detail.

Acknowledgments

This study, joint research led by the Institute of Environmental and Water Studies, Birzeit University, was executed through the financial support of the UNESCO-Flanders Program Grant No. 513RAB2041, which the writers gratefully acknowledge. The comments provided by anonymous reviewers are highly appreciated because they improved the quality of the article.

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