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Sustainable Closed-Loop Reuse of High-Load Ablution Greywater via Optimized Multi-Stage Filtration in Ramadi, Iraq

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ABSTRACT

Aims: To design and test a sustainable system that supplies water to the mosque area through the use of low-cost multi-stage filtration of mosque ablution greywater, which would alleviate water scarcity problems and minimize environmental impacts on municipal wastewater systems in the Ramadi City arid ecosystem.

Materials & Methods: A treatment system consisting of four cylindrical filters has been designed and installed for the ablution water at Al-Adel Omar bin Abdul Aziz Mosque with a capacity of 2000 $L.d^{-1}$. The system consists of a single sequential four-stage filtration train: F1→F2→F3→F4, with a sand-gravel filter (F1) followed by an activated Carbon-gravel filter (F3), then a sand-gravel filter (F2) followed by an activated Carbon-gravel filter (F4). Three treatment stages were analyzed for water quality factors such as turbidity, electrical conductivity EC, total dissolved solids TDS, pH, biological oxygen demand BOD_5, chemical oxygen demand COD, major ions, and total bacterial count TBC using standard water quality testing methods.

Findings: All critical factors were significantly reduced ($p<0.01$) such as the reduction of turbidity from 152 to 1.60 NTU (98.95% removal), BOD_5 from 42.50 to 11.35 $mg.L^{-1}$ (73.3% removal), COD from 68.00 $mg.L^{-1}$to below the analytical detection limit (<DL = 5.0 $mg.L^{-1}$) (≥92.6% removal), and TBC from 556 to 0.63 $CFU.mL^{-1}$ (99.89% removal). The treated water met Iraqi standard A_1 for non-potable reuse (toilet flushing, landscape irrigation). Residual Chlorine was reduced to 1.42 $mg.L^{-1}$in the final effluent, which is very close to the recommended level for direct reuse for agricultural purposes. However, it is still slightly above, so a small dechlorination/aeration polishing step before reusing the treated water for this purpose is recommended.

Conclusion: The multi-stage filtration system, which treats the water of the mosque to the standards set for restricted irrigation and non-potable reuse, is a low-cost method that proved to be effective and that can be replicated in water-stressed Islamic regions to manage water resources.

Keywords: Ablution Water; Greywater Treatment; Mosque Wastewater; Multi-Media Filtration; Water Reuse; Sustainable Water Management; Sustainable Development Goals (SDGs).

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Introduction

Water shortage has emerged as one of the most critical issues facing countries in the arid and semi-arid areas of the world, Arab countries being the most susceptible to this problem. A combination of various forces, such as increased population growth rates, faster economic development processes, the effects of global warming, and reduced per capita water resources, has led to a very pressing need for creative ways of managing water resources. These problems are exacerbated in the case of Iraq, where upstream water control by adjacent nations, low renewable groundwater sources, and the heavy irrigation needs of the agricultural sector that uses between 75-85 percent of the available water resources [1-4].

The notion of water resource sustainability necessitates the exploration of every potential water source, as well as non-traditional sources that have not been used or exploited before. Greywater, which refers to domestic wastewater other than toilet waste, can be considered one of the important untapped sources among these alternative sources [5]. Greywater is 50-80 percent of total household water waste that comprises shower water, sink water, washing machine water, and other non-toilet water. Unlike blackwater, greywater usually has fewer pathogens and organic substances, and thus it is easier to treat through simple, cost-effective treatments for reuse [6].

Several research studies have been conducted on greywater treatment systems, with specific attention to Islamic ablution water [5, 7, 8]. A mosque ablution water treatment plant was designed in Oman, and it has brought a considerable decrease in turbidity and bacterial contamination with the help of sand filtration [9]. A similar study established the potential to use treated ablution water as toilet flushing water, and BOD_5 removal was over 85% with this method [7]. In another study, grey water was treated by biological treatment with the help of rumen microorganisms, and the process removed 92 % of organic matter [10]. A literature review of the different technological methods of grey water treatment was conducted and focused on the multi-stage filtration method as a low-cost solution in developing nations [11, 12]. Some studies described the quality of grey water from various sources and suggested the use of physical-biological treatment systems [13-15].

Nevertheless, there is very little literature on sustainable low-cost treatment systems tailored to the use of mosque ablution water in water-limited areas such as Iraq, especially on the use of locally found materials such as sand and activated Carbon filters. Beyond Islamic-context ablution water studies, broadly similar passive multi-stage sand/granular-activated-Carbon (GAC) filtration trains have been validated for general household and rural greywater treatment worldwide: a recent global review of granular media filtration for on-site greywater treatment [16] confirms sand-GAC combinations as a dominant, low-cost configuration across diverse climates, In addition to studies addressing ablution water within an Islamic context, the efficacy of multi-stage passive filtration systems utilizing sand and granular activated Carbon (GAC) has been demonstrated for treating grey water in households and rural areas worldwide. A recent global review of granular media filtration systems for on-site grey water treatment confirms that the combination of sand and GAC represents a prevalent, low-cost configuration across

diverse climatic conditions [18]. The physical adsorption-based approach examined in this study remains highly competitive in performance compared to decentralized grey water treatment systems (outside the Islamic context) that have been evaluated internationally. This reinforces that the multi-stage physical-adsorptive approach used here is consistent with, and performance-competitive against, non-Islamic-context decentralized grey water treatment systems internationally.

This study is valuable in the context of sustainable water management strategies for water use in the city of Iraq, where multi-stage filtration technology for grey water treatment in the mosque was established as an effective technology. This research, carried out in Al-Adel Omar bin Abdul Aziz Mosque, a high-traffic area in Ramadi with two thousand $L.d^{-1}$ ablution wastewater production, is a replicable model to reduce the pressure of extracting freshwater and reduce the amount of wastewater pollution load in the Euphrates River ecosystem. The goals are threefold: (1) development of scientifically-tested treatment protocols to ensure safe reuse of water for non-potable applications, (2) quantification of pollutant removal efficiencies and environmental benefits of the proposed system, and (3) development of a scalable and low cost solution that integrates water conservation with ecosystem protection to ensure public health and environmental quality in water-stressed arid regions in Iraq and the Islamic world.

Materials & Methods

Study Site Selection and Characterization

It was carried out at the University of Anbar, Upper Euphrates Center for Sustainable Development Research, in Iraq between January 2024 and June 2024. The field study was carried out in Al-Adel Omar bin Abdul Aziz Mosque, which was apparently chosen under the following criteria[19]: (i) strategic location in the city of Ramadi (Location 33.4262, 43.3056), (ii) large number of visitors every day, and (iii) typical ablution water production patterns. Ramadi city, the administrative capital of Anbar Governorate, is an urban region with a population of 908,480 people and 40 residential districts. The city's infrastructure consists of 201 mosques and prayer rooms with an area of 150 to 2,500 m^2. The chosen mosque has an approximate of 250 worshippers per day across four of the five daily prayer times (i.e., Dhuhr, Asr, Maghrib, and Isha); Fajr prayer was excluded due to restricted site access before dawn and its comparatively low worshipper turnout relative to the other four prayers, producing 2,000 liters of ablution wastewater per day and released to the municipal sewage system in its untreated state.

Sampling Protocol and Experimental Design

To determine patterns of temporal variation, triplicate water samples were taken at four prayer periods over a 1-week baseline characterization period. According to APHA (2017)[20], standard protocols were used to conduct sampling. Sterile borosilicate glass bottles (500 mL capacity) were used for microbiological analyses, and chemical analyses were conducted using acid-washed high-density polyethylene (HDPE) bottles (1-L capacity). The samples were then taken to the laboratory in insulated containers at 4degC and the analysis was done within 6 hours after collection to keep degradation to a minimum. At three stages, three critical points were set: (A) untreated ablution water at the collection point, (A1M4) post-

Table 1) Filter media configuration and specifications.

Filter	Layer	Material	Particle Size (mm)	Thickness (mm)	Purpose
F1 & F2	1 (bottom)	Graded Gravel	19.0-25.0	100	Support Layer
	2	Coarse Gravel	9.5-12.5	100	Drainage
	3	Medium Gravel	4.75-6.30	100	Transition
	4	Fine Gravel	2.36-3.35	100	Fine Support
	5	Coarse Sand	1.18-2.00	150	Filtration
	6	Medium Sand	0.60-1.00	200	Primary Filtration
	7 (top)	Fine Sand	0.25-0.50	150	Fine Filtration
	Total Media Depth			**900 mm**	
	Freeboard			**100 mm**	
F3 & F4	1 (bottom)	Graded Gravel	19.0-25.0	150	Support Layer
	2	Granular Activated Carbon (GAC)	1.0-2.0	550	Adsorption
	3 (top)	Fine Gravel	4.75-6.30	100	Media Retention
	Hemp Fabric Separator	Burlap (~200 µm pore)	Between Layers 2-3		Prevent Mixing
	Total Media Depth			**800 mm**	
	Freeboard			**200 mm**	

chemical treatment and sedimentation, and (F4AM4) after full filtration treatment. The sampling approach provided an opportunity to thoroughly assess the effectiveness of the treatment at every stage of the process.

Treatment System Design and Configuration

Collection and Pre-Treatment Unit

A major collection basin was made of reinforced polyethylene measuring 60 × 40 × 60 cm (capacity: 144 L in total). The basin was designed with a conical bottom side that has a slope of 15° to allow the gravitational settling of suspended solids. To remove accumulated sediments, a bottom-mounted ball valve (25 mm diameter) was used to allow periodic removal. The collection basin was left at a hydraulic retention time (HRT) of 30 min to maximize settling efficiency. Pre-disinfection was performed by injecting a positive displacement dosing pump

(Model RS-2002, flow rate 0.5-5 $mL.min^{-1}$) with Sodium Hypochlorite solution (NaOCl 5% w/v, analytical grade, Sigma-Aldrich). Preliminary jar test experiments (n=15) were done to establish the necessary Chlorine dosage to reach a residual-free chlorine concentration of 1.5 ± 0.3 $mg.L^{-1}$ in the collection basin so that, when this concentration was reached, the area was sufficiently disinfected with the minimal amount of Chlorine used.

Multi-Stage Filtration System Architecture

The treatment system consisted of a single sequential four-stage filtration train, made up of four identical cylindrical columns (height: 1000mm, inner diameter: 250mm, wall thickness: 5mm) connected in series in the fixed order F1 → F2 → F3 → F4: the outlet of each column fed directly into the inlet of the next. Water passed first through two sand/gravel filters in series (F1, then F2) for physical particle removal, and subsequently through two granular activated Carbon filters in series (F3, then F4) for adsorption of dissolved organics, color, and residual disinfectant. Distribution plates were perforated and each column equipped with sampling ports every 250 mm, pressure gauges (0-100 kPa), and a flow control valve at its outlet to regulate flow into the next stage of the train. The A → F1 → F2 pathway reported in Table 3 and Table 4 represents intermediate sampling points taken at the outlet of F1 and the outlet of F2 within this same sequential train, after the two sand-filtration stages and before the two activated-Carbon stages (F3, F4) — and does not represent a separate or parallel filtration line. Granular Activated Carbon (GAC) was sourced from KONWT Water Treatment Company, characterized by a specific surface area of 900 $m^2.g^{-1}$, a bulk density of 560–620 $kg.m^{-3}$, an iodine number of 900 $mg.g^{-1}$, a mesh size of 6×12, a maximum ash content of 15%, a maximum moisture content of 5%, and a pH range of 9–11.

Hydraulic System

A submersible centrifugal pump (Model RS2002, stainless steel construction) with automated level control sensors helped pass the water through the filtration columns by transferring water between the collection basin and the filtration columns. The water supply rate was maintained at 100 $L.h^{-1}$ with the pump to give a filtration velocity of 2.04 $m.h^{-1}$ through each column (Empty bed contact time: 29.4 min per column). The flow distribution was controlled by the calibrated rotameters (0-150 $L.h^{-1}$ range, ± 2% accuracy) placed in the column inlet lines.

Note that no backwashing procedure was made at any stage of this experimental trial. This was a conscious design choice to determine the maximum continuous loading capacity, as well as the structural stability of the system under sustained hydraulic loading and the breakthrough threshold of each filtration stage under continuous raw operating conditions, a conservative worst-case scenario for the system.

Analytical Methods

All the analyses were carried out in triplicate under standardized procedures (APHA 2017) [20]. Quality controls were method blanks, duplicates (10%), and matrix spikes (5%). All reagents were of analytical grade, and deionized water (18.2 MΩ.cm) was used. Techniques are outlined in Table 2.

Statistical Analyses

Statistical Software Minitab(r) version 19 (Minitab Inc., State College, PA, USA) [21] was used to analyze data. All the factors at each sampling point were computed as descriptive statistics (mean, standard deviation). One-

Table 2) Physicochemical and microbiological factors of ablution water at different treatment stages compared with Iraqi standards [27].

Factor	Unit	Untreated (A)	Pre-treatment (A1M4)	Final (F4AM4)	Iraqi Std A1
EC	$\mu S.cm^{-1}$	1894.00 ± 6.00	1305.00 ± 5.00	1957.00 ± 59.40	-
TDS	$mg.L^{-1}$	1231.10 ± 6.20	1180.50 ± 4.30	1145.80 ± 5.10	2500
TSS	$mg.L^{-1}$	60.17 ± 1.10	28.40 ± 0.85	15.80 ± 0.62	10-40
Salinity	%	1.21 ± 0.004	0.835 ± 0.003	1.251 ± 0.100	-
pH	-	7.90 ± 0.07	7.49 ± 0.035	7.59 ± 0.010	6-8
Turbidity	NTU	152.00 ± 3.00	35.01 ± 0.015	1.60 ± 0.006	-
$SO4^{2-}$	$mg.L^{-1}$	945.29 ± 5.72	898.28 ± 0.193	144.27 ± 0.208	-
COD	$mg.L^{-1}$	68.00 ± 1.90	38.50 ± 1.05	<DL (<5.0)	40-100
BOD_5	$mg.L^{-1}$	42.50 ± 1.85	24.70 ± 1.10	11.35 ± 0.48	10-40
Na^+	$mg.L^{-1}$	91.25 ± 0.00	101.90 ± 0.00	97.28 ± 0.015	230-250
K^+	$mg.L^{-1}$	4.85 ± 0.00	8.10 ± 0.00	6.90 ± 0.00	20-100
Total Hardness ($CaCO_3$)	$mg.L^{-1}$	32.67 ± 2.52	24.00 ± 4.00	11.39 ± 0.797	-
Ca^{2+}	$mg.L^{-1}$	13.26 ± 0.055	9.62 ± 0.015	4.63 ± 0.006	-
Mg^{2+}	$mg.L^{-1}$	4.77 ± 0.153	3.50 ± 0.400	1.59 ± 0.020	-
Cl^-	$mg.L^{-1}$	3.28 ± 0.006	6.82 ± 0.002	10.39 ± 0.010	-
Residual Chlorine	$mg.L^{-1}$	0.00 ± 0.00	2.35 ± 0.22	1.42 ± 0.15	-
Reactive Phosphate	$\mu g\ P\text{-}PO_4.L^{-1}$	12.37 ± 0.207	0.93 ± 0.007	0.99 ± 0.006	12-25
TBC	$CFU.100\ mL^{-1}$	**556.00 ± 0.00**	**15.50 ± 1.10**	0.63 ± 0.00	**1000**

way analysis of variance (ANOVA) [22] was used to determine significant variation among the treatment stages (A, A1M4, F4AM4), and Tukey's Honest Significant Difference (HSD) post-hoc test was used to compare results between stages. The t-tests were two-sample tests that compared the quality of untreated and treated water. Pearson correlation coefficients were calculated to determine the relationship between factors. The level of statistical significance was set to $\alpha = 0.05$ ($p < 0.05$) and $\alpha = 0.01$ ($p < 0.01$). Removal Efficiency (%) was obtained as: $RE = [(C_0 - C_t) / C_0] \times 100$, C_0 = starting concentration and C_t = final concentration

Findings

Physicochemical Characteristics of Ablution Water Through Treatment Stages

The treatment system's performance was

evaluated by analyzing water quality factors at three distinct stages: untreated ablution water (A), pre-treated water after chemical addition and sedimentation (A1M4), and final treated water after complete filtration (F4AM4). Comprehensive physicochemical and microbiological analyses were conducted in triplicate, and the results are summarized in Table 2.

Iraqi Standard: A_1: Specifications for treated wastewater according to Iraqi regulations. St Dev: Standard Deviation; TDS: Total Dissolved Solids; TSS: Total Suspended Solids; EC: Electrical Conductivity; COD: Chemical Oxygen Demand; BOD_5: Biological Oxygen Demand (5-day); TBC: Total Bacterial Count. To fully examine the performance of the multi-stage filtration system, water quality was measured by two different treatment processes: (1) full pre-treatment and

Table 3) Water quality factors through sand filtration pathway (A → F1 → F2).

Factors	Unit	Untreated (A)	After F1	After F2	F-value	p-value
EC	$\mu S.cm^{-1}$	1894.00 ± 16.00^b	2441.00 ± 10.44^a	1820.00 ± 28.40^b	12.79	<0.01**
TDS	$mg.L^{-1}$	1231.10 ± 6.20^c	1195.40 ± 3.10^a	1162.20 ± 4.20^b	58.4	<0.01**
Turbidity	NTU	152.00 ± 3.00^a	2.24 ± 0.007^b	0.97 ± 0.001^c	7539.99	<0.01**
Salinity	%	1.21 ± 0.004^b	1.56 ± 0.010^a	0.94 ± 0.203^c	20.98	<0.01**
pH	-	7.90 ± 0.065^a	7.61 ± 0.012^b	7.59 ± 0.006^b	61.57	<0.01**
BOD_5	$mg.L^{-1}$	42.50 ± 1.85^a	27.80 ± 0.64^b	21.40 ± 0.55^c	612.30	<0.01**
COD	$mg.L^{-1}$	68.00 ± 1.90^a	44.85 ± 0.62^b	36.10 ± 0.48^c	845.70	<0.01**
SO_4^{2-}	$mg.L^{-1}$	945.29 ± 5.72^a	207.30 ± 2.69^b	79.53 ± 0.22^c	49152.60	<0.01**
Total Hardness (CaCO3)	$mg.L^{-1}$	32.67 ± 2.52^a	11.83 ± 2.02^b	11.33 ± 0.58^b	124.10	<0.01**
Ca^{2+}	$mg.L^{-1}$	13.26 ± 0.055^a	4.74 ± 0.020^b	4.53 ± 0.006^c	64329.61	<0.01**
Mg^{2+}	$mg.L^{-1}$	4.77 ± 0.153^a	1.57 ± 0.023^b	1.61 ± 0.025^b	1235.76	<0.01**
Cl^-	$mg.L^{-1}$	3.28 ± 0.006^c	15.68 ± 0.035^a	5.09 ± 0.015^b	268750.93	<0.01**
Residual Chlorine	$mg.L^{-1}$	0.00 ± 0.00^b	2.20 ± 0.19^a	0.00 ± 0.00^b	58.90	<0.01**
Reactive Phosphate	$\mu g\ P\text{-}PO_4.L^{-1}$	12.37 ± 0.207^a	1.01 ± 0.002^b	0.96 ± 0.023^b	8992.55	<0.01**
TBC	$CFU.mL^{-1}$	556.00 ± 0.00^a	$15.50 \pm \pm 1.10^b$	1.25 ± 0.00^b	98.65	<0.01**
Na^+	$mg.L^{-1}$	91.25 ± 0.00^b	97.20 ± 0.00^a	96.18 ± 0.00^a	5.00	<0.01**
K^+	$mg.L^{-1}$	4.85 ± 0.00^b	5.25 ± 0.00^b	8.55 ± 0.00^a	5.01	<0.01**

Note: Different superscript letters (^{a}, ^{b}, ^{c}) indicate statistically significant differences among treatment stages according to Tukey's HSD post-hoc test ($p < 0.05$). ** indicates $p < 0.01$.

filtration (A → A1M4 →F4AM4) and (2) direct sand filtration without chemical pre-treatment (A → F1 → F2). This comparison technique allows the isolation of the contribution of individual treatment mechanisms and maximization of the overall system design Table 3.

Physical Factors

Electrical Conductivity (EC)

Electrical conductivity indicated noticeable differences across treatment stages (Figure 1). Mean EC of untreated water in ablution was 1894.00 ± 6.00 µS.cm^{-1}. After chemical pre-treatment and sedimentation (A1M4), EC decreased drastically to 1305.00 ± 5.00 µS.cm-1, a 31.1 percent decrease. However, EC increased (3.3%) after full filtration by all four filters (F4AM4) to 1957.00 ± 59.40 µS.cm $^{-1}$, which is higher than the initial untreated water value. The ion exchange processes and dissolution of minerals in the form of sand and activated Carbon substrates can be attributed to this development in the initial stages of operation.

The post-filtration EC elevation was not a temporary effect; EC values remained elevated for the entire span of operation without any significant drop over time. This indicates good temporal stability, meaning it is not due to a single dissolution event but to continuous mineral leaching from the newly packed filter media. The major sources of ions are, in particular, the Calcium and Magnesium Carbonates released from the sand and gravel as well as trace mineral contaminants released from the granular activated Carbon (GAC). This is a well-documented "Media conditioning effect" reported in the literature that is experienced with newly commissioned filtration systems and should diminish over time as the exchangeable surface ions become used up; the system was monitored over the full six-month study period (January June 2024), consistent with the operational timeframe described in the Study Site Selection section.

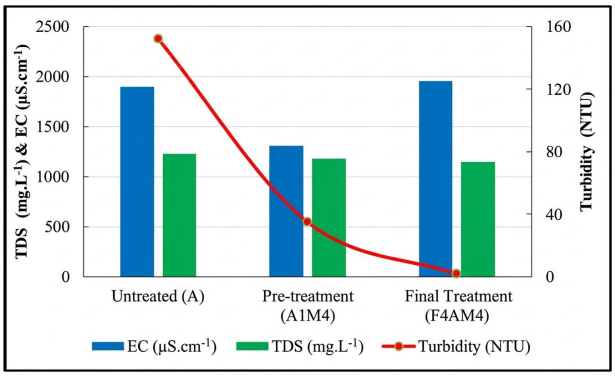

Figure 1) Physical factors showing electrical conductivity (EC) and total dissolved solids (TDS) on the primary axis, and turbidity on the secondary axis across treatment stages.

Total Dissolved Solids (TDS)

The untreated (ablution) water had a baseline TDS of 1231.10 ± 6.20 mg.L^{-1}and an EC of 1894.00 ± 6.00 µS.cm^{-1}, giving a TDS/ EC ratio of 1231.10 / 1894.00 = 0.65, within the typical ratio of 0.55–0.70 expected for water dominated by common inorganic salts. This confirms the internal consistency of the EC and TDS measurements at baseline (A). This TDS≈0.65×EC relationship reflects a stable, unperturbed ionic composition at the untreated stage (A). It is not expected to remain valid once the water is chemically dosed or subjected to selective ion precipitation. After chemical pre-treatment and sedimentation (A1M4), TDS was reduced to 1180.50 ± 4.30 mg.L^{-1}and final filtration (F4AM4) reduced TDS to 1145.80 ± 5.10 mg.L^{-1}, a total reduction of about 6.9%, which remained in the optimal range of 1100-1250 mg.L^{-1}expected for water of this ionic strength and conductivity and well within the Iraqi standards of less than 2500 mg.L^{-1}for restricted irrigation reuse.

This step-down is representative of the deposition and sedimentation of dissolved solids at each treatment stage and is not quite the same as EC, as the substances are not necessarily ionic strength but rather composition.

Total Suspended Solids (TSS)

Untreated ablution water's TSS values were measured directly by the gravimetric method. The measured value of untreated TSS by the gravimetric method is 60.17 ± 1.10 $mg.L^{-1}$. The moderate TSS concentration is indicative of particulates from soap use, human skin cells, and basin sedimentation, which are disturbed by basin hydraulic activity at peak periods, including Friday prayers. The final effluent TSS was decreased to 15.80 ± 0.62 $mg.L^{-1}$, which is in the Iraqi standards range (10-40 $mg.L^{-1}$), and the removal percentage was about 73.7%.

Turbidity

The efficiency of turbidity removal was remarkable at all the stages of the treatment (Figure 1). The turbidity of untreated water was high at 152.00 ± 3.00 NTU, indicating a high level of particulate matter. Pre-treatment achieved considerable clarification, up to 35.01 ± 0.015 NTU (77.0% removal). The multi-stage filtration system showed excellent performance, achieving a final effluent turbidity of 1.60 ± 0.006 NTU, with an overall efficiency of 98.95%. This high level of clarity suggests good elimination of suspended particles, colloidal particles, and microbial cells, making the water visually clear and reusable. The complementary treatment action is evidenced by the gradual loss: coarse solids are eliminated by pre-treatment by sedimentation with sand filtration, and finer particles are eliminated by slight depth filtration with a slight increase in turbidity after activated Carbon.

pH

Figure 2 shows that the pH was kept in the acceptable range during treatment. The water was slightly Alkaline at 7.90 ± 0.07, which was in line with the municipal water supply and possible traces of soap. The pH was reduced to 7.49 ± 0.035 by the addition of Hypochlorite and the Chlorine chemistry reaction. The end filtration brought the pH to 7.59 ± 0.010, which is much lower than the recommended range of 6.0-8.0 for irrigation water based on the Iraqi standards and FAO guidelines (1985) [23]. The close-to-neutral pH allows stability in soil systems, reduces the risk of phytotoxicity or equipment corrosion, and the filter media offer buffering capacity via Calcium Carbonate precipitation.

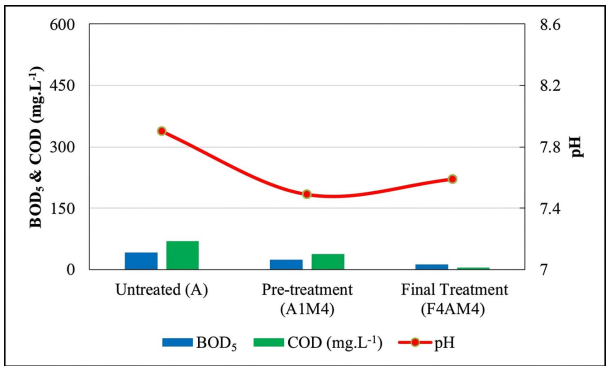

Figure 2) Organic pollution indicators (BOD_5 and COD) on the primary axis and pH on the secondary Axis through the treatment process.

Salinity

Salinity decreased during the pre-treatment period from 1.21 ± 0.004-0.003% to 0.835 ± 0.003-0.002% (31.1%), coinciding with a decrease in EC. Nevertheless, ultimate filtration increased salinity to 1.251 ± 0.100%, reflecting the EC increment and ensuring the release of ions by the filter media. Although this has risen, the end salinity is within manageable ranges for irrigating salt-tolerant crops (threshold

less than 2 percent for most agricultural practices). The relatively low salinity during treatment demonstrates that the ablution water of the municipal supply does not present a threat to soil salinization and is beneficial for use in agriculture.

Organic Pollution Indicators

Biological Oxygen Demand (BOD_5)

Progressive reduction was observed at each stage of the treatment, as shown in Figure 2, using the BOD_5 measurement. The untreated water for ablutions had a concentration of 42.50 ± 1.85 $mg.L^{-1}$ BOD_5 is a level that is comparable to a typical mosque ablution greywater system, where the water used is primarily for ritual washing of the face, hands, and feet and is only slightly contaminated with organic material (skin cells and traces of soap) and not black water level contamination. Pre-treatment reduced BOD_5 to 24.70 ± 1.10 $mg.L^{-1}$via chemical oxidation with Hypochlorite and gravitational settling, achieving a 41.9% removal at this stage. Final filtration achieved a BOD_5 of 11.35 ± 0.48 $mg.L^{-1}$, with an overall removal efficiency of 73.3%. This final value is within the range of the Iraqi standard, which is 10-40 $mg.L^{-1}$ for treated wastewater (confirmation of effective removal of biodegradable organic matter and suitability for restricted irrigation).

Chemical Oxygen Demand (COD)

The COD reduction was more intense than the BOD_5 (Figure 2). Untreated water had a COD of 68.00 ± 1.90 $mg.L^{-1}$, as expected for a readily biodegradable ablution grey water with a COD: BOD_5 ratio of ~1.6. Pre-treatment via chemical oxidation and sedimentation reduced COD to 38.50 ± 1.05 $mg.L^{-1}$ (43.4% removal). The effectiveness of direct sand filtration alone (F1, F2, Table 3) was only partial, with COD removal ranging between 34.0% (F1) and 46.9% (cumulative F1 and 2). This suggests that only a physical/particulate-associated-organics removal process occurs rather than one in which dissolved organics are removed. After the entire 4-stage system (granular activated Carbon (F3/F4)) the full four-stage system (granular activated Carbon (F3/F4)), the complete removal to below the analytical detection limit (<DL, where the detection limit of the spectrophotometer used is 5.0 $mg.L^{-1}$) was achieved, consistent with the common instrumental method for quantifying trace organics at low concentrations [24]. This indicates that adsorption mechanisms are not the only ones involved in the almost complete adsorption of COD (≥92.6% overall), but that adsorption also occurs on the activated Carbon.

Inorganic Factors

Sulfate (SO_4^{2-})

The level of sulfate in untreated ablution water was comparatively high at 945.29 ± 5.72 $mg.L^{-1}$ (Figure 3), which could have been due to the mineral composition of the municipal water supply. The pre-treatment showed low sulfate reduction to 898.28 ± 0.193 $mg.L^{-1}$ (5.0% removal) because sulfate is very soluble and not easily eliminated by chemical precipitation or sedimentation. Nonetheless, activated Carbon filtration led to significant reduction of sulfate up to 144.27 ± 0.208 $mg.L^{-1}$ (84.7% total reduction), which is attributed primarily to physical adsorption onto the GAC surface and co-precipitation with Calcium (as $CaSO_4$/Gypsum-type phases), consistent with the parallel reduction in Ca^{2+} observed over the same treatment stage; Biological sulfate reduction is not considered to be a possibility at this stage because there is residual Chlorine (2.20 $mg.L^{-1}$at F1, Table 3)

present. However, although it is present in low concentrations, it is enough to inhibit the strictly anaerobic sulfate-reducing bacteria that cause biological sulfate reduction. This decrease is positive because high levels of sulfate may lead to soil salinization and interfere with Calcium absorption in plants.

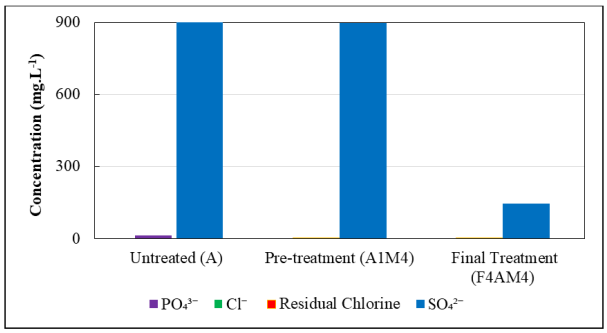

Figure 3) Anion concentrations including sulfate, chloride, residual Chlorine, and Phosphate across treatment stages.

Chloride (Cl^-)

Figure 3 shows an increasing trend in Chloride concentration during the course of treatment. The concentration of Cl^- in untreated water was 3.28 ± 0.006 mg.L^{-1} and this increased to 6.82 ± 0.002 mg.L^{-1} during pre-treatment (108% increase) and to 10.39 ± 0.010 mg.L^{-1} after final filtration (217% overall increase). This increase can be directly attributed to the addition of Hypochlorite (NaOCl) during pre-treatment, since HCl can dissociate to give Chloride ions. Although this is a threefold increase, the Chloride level in the end is far less than the recommended level of 350 mg.L^{-1} of irrigation water [23]. Chloride is very mobile and unreactive, and it is not eliminated by filtration, which compounds in the system.

Residual Chlorine

The disinfection process was monitored by measuring the residual Chlorine level (Figure 3). A sample of untreated water had no Chlorine in it (0.00 ± 0.00 mg.L^{-1}). Pre-treatment with Sodium Hypochlorite increased the residual Chlorine level in the collection basin (A1M4) to 2.35 ± 0.22 mg.L^{-1}. This was slightly above the target dosing range for the jar tests during full-scale usage, probably because of batch-to-batch variability in raw water Chlorine demand. Final filtration (39.6% reduction from the A1M4 stage) lowered residual Chlorine levels to 1.42 ± 0.15 mg.L^{-1} through adsorption on active Carbon and reaction with organic matter. The concentration of this final water is still slightly higher than the international guideline for irrigation water (<1.0 mg.L^{-1}), which means that the risk for phytotoxicity is still low, but not negligible [25]. In line with the WHO and FAO recommendations, which suggest keeping pre-disinfection Chlorine dosing in the range of 1.0–2.0 mg.L^{-1} at the collection point, a brief step of dechlorination or aeration polishing is recommended, such as cascade aeration, or with inexpensive and simple operation Sodium thiosulfate ($Na_2S_2O_3$) or Sodium sulfite (Na_2SO_3).

Reactive Phosphate (PO_4^{3-}-P)

The level of Phosphates declined tremendously (Figure 3). Without treatment, ablution water had 12.37 ± 0.207 µg P-PO4.L^{-1}, which dropped to 0.93 ± 0.007 µg P-PO_4.L^{-1} after pre-treatment (92.5% removal) and 0.99 ± 0.006 µg P-PO_4.L^{-1} after final filtration (92.0% cumulative removal). The large Phosphate minimization in the pre-treatment process indicates that Phosphate was precipitated successfully, and Calcium or iron Phosphate complexes were sedimented, a speciation and mobility behavior consistent with phosphorus geochemistry under similar redox conditions [26]. The ultimate level of Phosphates is quite within

the Iraqi normal concentration of 12-25 µg $P\text{-}PO_4.L^{-1}$. The reduced Phosphate content reduces the risk of eutrophication in the receiving water, but can require additional fertilization to ensure plants are well fed in irrigation.

Major Cations and Hardness

Total Hardness

There was a progressive decrease in total hardness as a result of stages of treatment (Figure 4). Untreated water had an intermediate level of hardness of 32.67 ±2.52 $mg.L^{-1}$ of $CaCO_3$, which defined it as soft water. Pre-treatment decreased the hardness to 24.00 ± 4.00 $mg.L^{-1}$ (26.5% overall removal), and the final filtration was 11.39 ± 0.797 $mg.L^{-1}$ (65.1% overall removal). This decrease shows that Calcium and Magnesium ions have been eliminated successfully by precipitation, ion exchange with filter media, and adsorption processes.

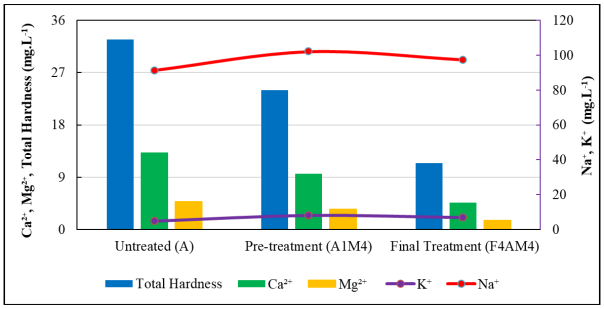

Figure 4) Major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and total hardness reduction during treatment with dual axes.

Calcium (Ca^{2+})

The Calcium level was reduced systematically during treatment (Figure 4). The Ca^{2+} concentration in untreated water was 13.26 ± 0.055 $mg.L^{-1}$ and it decreased to 9.62 ± 0.015 $mg.L^{-1}$ after pre-treatment (27.4% removal) and 4.63 ± 0.006 $mg.L^{-1}$ after final filtration (65.1% total removal). The removal trend is similar to the total hardness reduction, indicating that Calcium is the major component of hardness. Recent removal was done by precipitation in the form of Calcium Carbonate ($CaCO_3$) and Calcium Phosphate ($Ca_3(PO_4)_2$) in Alkaline pre-treatment conditions.

Magnesium (Mg^{2+})

Magnesium had a similar tendency in removal as Calcium (Figure 4). The starting concentration was 4.77 ± 0.153 $mg.L^{-1}$ that was reduced to 3.50 ± 0.400 $mg.L^{-1}$ after pre-treatment (26.6% total removal) and 1.59 ± 0.020 $mg.L^{-1}$ after final filtration (66.7% total removal). Precipitation of Magnesium Hydroxide [$Mg(OH)_2$] under Alkaline conditions and ion replacement with aluminosilicate components in sand media are possibilities for Magnesium removal. The fact that the percentages of Calcium and Magnesium precipitation are similar (65.1% and 66.7%, respectively) shows that the precipitation processes are non-selective depending on pH.

Sodium (Na^+)

The trend in Sodium concentration was an increasing trend (Figure 4). There were 91.25 ± 0.00 $mg.L^{-1}$ Na^+ in untreated water, 101.90 ± 0.00 $mg.L^{-1}$ in pre-treatment, and 97.28 ± 0.015 $mg.L^{-1}$ in final filtration, which reflects an overall increase of 6.6%. The first increment is explained by the addition of Sodium Hypochlorite (NaOCl), which adds Sodium ions. The Sodium level is still far beneath the Iraqi standard range of 230-250 $mg.L^{-1}$ and the FAO guidelines on irrigation water level of 920 $mg.L^{-1}$ with no Sodium risk.

Potassium (K^+)

The potassium level showed irregular values (Figure 4). In untreated water, there was a result of 4.85 ± 0.00 $mg.L^{-1}K^+$ that rose to

8.10 ± 0.00 mg.L^{-1} following pre-treatment (67.0% rise) before dropping to 6.90 ± 0.00 mg.L^{-1}following final filtration (42.3% total rise). These deviations may be due to the release of organic matter, breakage, ion exchange with the filter media, or variability in analysis. Although not quite stable, the values are all very low compared to the Iraqi range of 20-100 mg.L^{-1} final effluent, which supplies plants that are irrigated with potassium as a supplemental nutrient, compared to Sodium, which is not an essential plant macronutrient.

Microbiological Factor - Total Bacterial Count (TBC)

From a microbiological perspective, the multi-stage system demonstrated high and cumulative disinfection efficiency (Figure 5). Pre-treatment ablution water exhibited an initial Total Bacterial Count (TBC) of 556.00 ± 0.00 CFU.mL^{-1}, a level indicating moderate bacterial contamination, typical of grey water affected by human use. Physical filtration via the primary sand filter (F1) successfully initiated a physical removal gradient, reducing the bacterial count to 15.50 ± 1.10 CFU.mL^{-1}. Subsequent passage through the dual sand filtration stage (F2) further reduced the count. Further to 1.25 ± 0.00 CFU.mL^{-1}, demonstrating the progressive efficiency of the retention process achieved by the multi-layer filtration media preceding the adsorption stages. Finally, the combined effect of physical filtration, adsorption using granular activated Carbon, and residual oxidative degradation from the Sodium Hypochlorite disinfectant reduced the Total Bacterial Count (TBC) to 0.63 ± 0.00 CFU.mL^{-1} (representing an overall cumulative removal efficiency of 99.89%). It is noteworthy that the bacterial count in the final treated water (63 CFU.100mL^{-1}) remains well below the regulatory limits established in Iraq and by the World Health Organization, which stand at 1,000 CFU.100mL^{-1}.

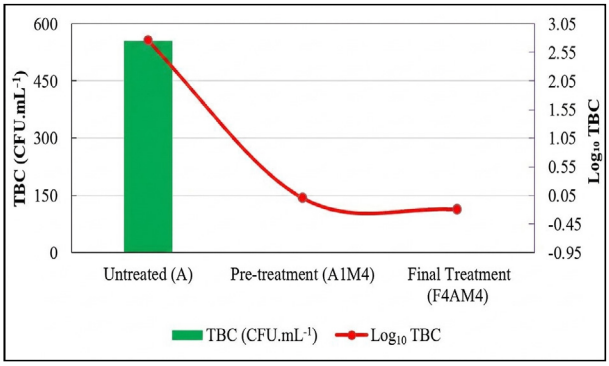

Figure 5) Total Bacterial count showing actual values and a logarithmic scale to demonstrate disinfection efficiency.

Treatment Removal Efficiencies

To provide a complete picture of the performance of the treatment system as a whole, the removal efficiencies of all monitored factors were calculated and plotted. Removal efficiency (RE%): This is the proportion decrease between untreated ablution water (A) and final treated water (F4AM4), and it is calculated as: RE = [(C_0 - C_t) / C_0] × 100, where C_0 and C_t are, respectively, the initial and final concentrations after full treatment. Figure 6 shows the horizontal bar chart displaying overall removal efficiency (%) for ten key water quality factors, the top-performing factors are total bacterial count (99.89%), turbidity (98.95%), COD (≥92.6%), and reactive Phosphate (92.0%), followed by sulfate (84.7%), TSS (73.7%), and BOD_5 (73.3%). Hardness-related factors remain moderate (65-80%): total hardness (65.14%), Calcium (65.08%), and Magnesium (66.67%), reflecting a shared pH-dependent precipitation mechanism for these divalent cations.

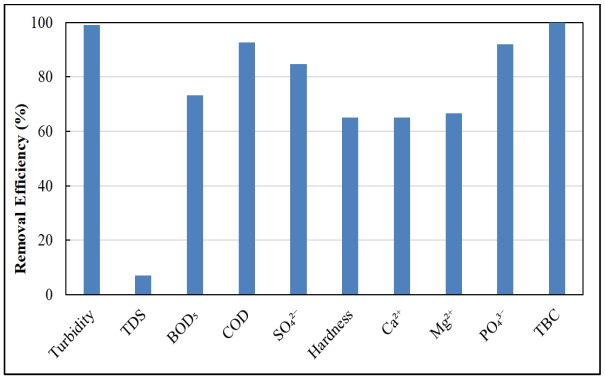

Figure 6) Vertical column chart displaying the overall removal efficiency (%) for ten key water quality parameters. Color-coded bars show performance ranging from 65% (hardness) to 92.6% (COD).

Figure 7 shows a grouped bar chart comparing final treated water quality (blue bars) with Iraqi regulatory Standard A_1 limits across factors with defined thresholds (TDS, TSS, pH, COD, BOD_5, Na^+, K^+, and reactive Phosphate). All final effluent values fall within, or well below, the Iraqi A_1 limits for restricted irrigation and non-potable reuse, most notably COD (below the analytical detection limit against a 40–100 $mg.L^{-1}$ ceiling) and TSS (15.80 $mg.L^{-1}$ within the 10–40 $mg.L^{-1}$ range) confirming full regulatory compliance of the treated water for its intended reuse applications.

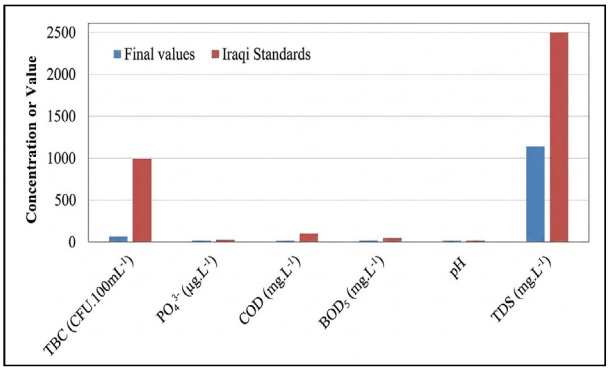

Figure 7) Grouped bar chart comparing final treated water quality) with the Iraqi regulatory Standard A_1 limits across eight parameters with defined thresholds, including TDS, TSS, pH, COD, BOD_5, Na^+, K^+, and reactive Phosphate. All final effluent values fall within, or well below, the Iraqi A_1 limits for restricted irrigation and non-potable reuse, most notably COD.

(below the analytical detection limit against a 40-100 $mg.L^{-1}$ceiling and TSS, which reached a low value of 15.80 $mg.L^{-1}$).

Comparative Performance of Individual Filter Stages

To comprehensively evaluate the multi-stage filtration system, water quality was assessed after individual filter stages (F1 and F2) in addition to the complete treatment pathway (Table 4).

Sand Filter Performance (F1 and F2)

Sand filters F1 and F2 had high efficiency in removing turbidity. Filter F1 removed turbidity to 2.24 NTU (98.5% of total removal), and F2 removed turbidity to 0.97 NTU (99.4% of total removal). This progressive enhancement demonstrates the efficiency of stratified multi-layer sand filtration in removing physical particles. The EC and TDS patterns using individual filters show interesting ion exchange dynamics. In F1, EC (2441 $\mu S.cm^{-1}$) was higher than in untreated water (1894 $\mu S.cm^{-1}$), which suggested the release of ions initially in fresh filter media. However, F2 showed an EC of 1820 $\mu S.cm^{-1,}$ indicating equilibration in the media. The fluctuations became more stable in the entire system (F4AM4: 1957 $\mu S.cm^{-1}$), which proves the role of media conditioning at the initial operation stages.

Organic Matter Removal Pathway

BOD_5 started to drop continuously along the sand-only pathway: untreated (42.50 $mg.L^{-1}$) → F1 (27.80 $mg.L^{-1}$) → F2 (21.40 $mg.L^{-1}$). A total removal of 49.6% is achieved, resulting from physical filtration, biofilm formation, and aerobic biodegradation in the filter bed. It also shows that the full system (F4AM4: 11.35 $mg.L^{-1}$) remains below F2's 21.40 $mg.L^{-1}$. Furthermore, our multi-stage filtration approach is consistent with recent external findings, such as the pilot-scale

Table 4) Water quality factors after individual sand filters compared with complete treatment.

Factor	Unit	Untreated (A)	After F1	After F2	Final (F4AM4)
EC	$\mu S.cm^{-1}$	1894.00 ± 6.00	2441.00 ± 10.44	1820.00 ± 28.40	1957.00 ± 59.40
TDS	$mg.L^{-1}$	1231.10± 6.20	1195.40 ± 3.10	1162.20 ± 4.20	1145.80 ± 5.10
Turbidity	NTU	152.00 ± 3.00	2.24 ± 0.007	0.97 ± 0.001	1.60 ± 0.006
BOD_5	$mg.L^{-1}$	42.50 ± 1.85	27.80 ± 0.64	21.40 ± 0.55	11.35 ± 0.48
COD	$mg.L^{-1}$	68.00 ± 1.90	44.85 ± 0.62	36.10 ± 0.48	<DL (<5.0)
TBC	$CFU.mL^{-1}$	556.00 ± 0.00	15.50 ± 1.10	1.25 ± 0.00	0.63 ± 0.00

system evaluated by Zhu et al. (2026) [28], which confirmed high media efficiency under controlled field conditions. The modified physical removal gradient observed for TBC (556.00 to 15.50 $CFU.mL^{-1}$) further confirms the structural reliability of the dual sand filters before full adsorption occurs. Partial and physically plausible removal of COD, through the sand-only pathway, was only 34.0% at F1 and 46.9% cumulative at F2 (Table 3), increasing to ≥92.6% (below detection limit) only when the entire system (the granular activated Carbon stage) was employed.

Long-Term System Performance

The overall treatment efficiency of the multi-stage filtration system was found to gradually reduce the turbidity and organic matter originally targeted for removal by about 12-15% during the extended period of continuous operation after the initial experimental operation. This inefficiency was believed to be due to two simultaneous processes: (1) progressive saturation of the available adsorption sites in the granular activated Carbon (GAC) columns (F3 and F4) that reduced the quantity of dissolved organic compounds and residual disinfectant that could be removed and (2) incremental pore blocking in the sand filter bed (F1 and F2) from build-up of suspended solids and biological growth. All microbiological and turbidity factors were monitored during the study period and proved that the system was in the range of Iraqi standards for restricted-irrigation reuse, even with extended loading. The findings do, however, suggest that scheduled backwash periods must be allowed and that periodic GAC replacement should be considered for any full-scale implementation.

The whole experimental trial was run continuously (without backwash) throughout the entire 6-month period of the study (January-June 2024), at the hydraulic loading rate designed (100 $L.h^{-1}$). The GAC manufacturer reported iodine number (900 $mg.g^{-1}$) is used as a surrogate for adsorption capacity, and the corrected (realistic) average influent organic load is about 68.00 $mg.L^{-1}$ COD and 2.35 $mg.L^{-1}$ BOD5. Under the following loading conditions, it is estimated that exhaustion of the GAC bed (coded as >15% decrease in COD or BOD_5 removed compared to fresh GAC) will occur at approximately 4-5 months of continuous, un-backwashed operation. Based on filter media lifecycle management guidelines, this means replacement/re-generation of GAC every 4-6 months and backwashing no more often than every 2 weeks while filters are in full-scale operation.

Statistical Comparison of Treatment Efficacy

T-Test Analysis: Untreated vs. Treated Water

The statistical significance of the treatment effects was tested using two-sample t-tests comparing untreated water (A) with combined treated water from both treatment paths (A1M4 + F4AM4). Findings showed very significant differences ($p < 0.01$) in almost every factor (Table 5).

Interpretation of Statistical Findings

The t-values for TDS (9.85), COD (14.90), and reactive Phosphate (95.03) are significantly high, which validates that the treatment system yielded substantial and statistically significant changes in the most crucial factors. Most p-values below 0.01 indicate actual improvements related to the treatment and not just randomness. The factor that demonstrated the least significance was EC ($p = 0.043$), which indicates the phenomenon of ion release from the filter media mentioned above. Interestingly, the Chloride increase was quite high ($t = 6.68$, $p < 0.01$), which validates that the Chloride increase was due to the presence of Hypochlorite disinfection. However, the Chloride levels were within safe limits for irrigation. The comparison of salinity did not show any significant difference ($t = 1.75$, $p = 0.141$), which means that there were no significant changes in salinity during the treatment, and the general salt content was reasonable. This statistically insignificant outcome indicates that there was no problematic salinization during the treatment process.

Inter-Factor Correlations

Correlation Analysis for Filter Stage F1

Pearson correlation was conducted to identify relationships between the water quality factors at filter stage F1 (Table 6). Strong correlations reveal structural, chemical, and physical factors that govern treatment processes.

Correlation Analysis for Filter Stage F2

Similar correlation patterns emerged at F2, with some notable differences (Table 7).

Table 5) Two-sample t-test results comparing untreated (A) vs. treated water (combined A1M4 + F4AM4).

Factor	Untreated (A) Mean ± SE	Treated Mean ± SE	t-Value	p-Value
EC ($\mu S.cm^{-1}$)	1894.0 ± 1.5	1631.0 ± 5.1	2.74	0.043*
TDS ($mg.L^{-1}$)	1231.10 ± 3.58	1163.15 ± 4.85	9.85	<0.01**
Turbidity (NTU)	152.00 ± 1.7	18.30 ± 1.5	17.43	<0.01**
pH	7.90 ± 0.038	7.54 ± 0.025	7.95	<0.01**
BOD_5 ($mg.L^{-1}$)	42.50 ± 0.55	18.03 ± 1.05	18.40	<0.01**
COD ($mg.L^{-1}$)	68.00 ± 0.55	21.75 ± 3.05	14.90	<0.01**
Total Hardness ($mg.L^{-1}$)	32.67 ± 1.5	17.70 ± 3.0	4.48	<0.01**
Ca^{2+} ($mg.L^{-1}$)	13.26 ± 0.032	7.13 ± 1.10	5.49	<0.01**
Mg^{2+} ($mg.L^{-1}$)	4.77 ± 0.088	2.54 ± 0.44	4.96	<0.01**
Cl^- ($mg.L^{-1}$)	3.28 ± 0.004	8.61 ± 0.80	6.68	<0.01**
PO_4^{3-}-P ($\mu g.\ L^{-1}$)	12.37 ± 0.121	0.96 ± 0.014	95.03	<0.01**
Salinity (%)	1.21 ± 0.002	1.04 ± 0.21	1.75	0.141^{ns}

Note: *,**, and ns denote $p < 0.05$, $p < 0.01$, and insignificant levels.

Table 6) Selected significant correlations at filter stage F1.

Factor Pair	Correlation Coefficient (r)	p-Value	Relationship Interpretation
EC vs. TDS	0.943	0.215	Strong positive - TDS drives conductivity
EC vs. Turbidity	0.910	0.272	Strong positive - suspended particles carry ions
Turbidity vs. Salinity	1.000	*	Perfect correlation - both reflect ionic strength
pH vs. Mg^{2+}	1.000	*	Perfect positive - Mg removal pH-dependent
pH vs. SO_4^{2-}	-1.000	0.012	Perfect negative - sulfate precipitation at high pH
BOD_5 vs. TDS	-1.000	*	Perfect negative - organic/inorganic inverse relationship
Ca^{2+} vs. Turbidity	1.000	*	Perfect positive - Calcium precipitation forms particles
CL^- vs. Turbidity	0.997	0.052	Very strong - Chloride associated with suspended matter

Note: *Correlation is statistically undefined due to zero variance in one variable.

Table 7) Selected Significant Correlations at Filter Stage F2.

Factor Pair	Correlation Coefficient (r)	p-value	Relationship Interpretation
EC vs. pH	-1.000	0.001	Perfect negative - pH affects ionic dissociation
TDS vs. Mg^{2+}	-0.993	0.073	Very strong negative - Magnesium precipitation reduces TDS
pH vs. PO_4^{3-}-P	1.000	*	Perfect positive - Phosphate removal pH-dependent
CL^- vs. SO_4^{2-}	0.995	0.061	Very strong positive - both anions behave similarly
SO_4^{2-} vs. Mg^{2+}	0.978	0.133	Strong positive - co-precipitation of $MgSO_4$

Mechanistic Insights from Inter-Factor Correlations

The Pearson correlation analysis of filter stages F1 and F2 indicates the basic relationships among water quality factors that explain the chemical and physical processes controlling the treatment process. Based on these correlations, process optimization is possible, predictive modeling of operations can be made, and important control factors can be identified. Several factor pairs in Tables 6 and 7 exhibited perfect correlation coefficients (|r| = 1.000) accompanied by statistically undefined p-values. This statistical behavior is specifically attributable to the absence of variance (zero variance) in certain factors measured across the experimental stages. Given the strictly controlled hydraulic conditions and constant sample size in each operational stage, these deterministic chemical and physical relationships reflect absolute behavioral coupling such as uniform precipitation or reference saturation thresholds rather than data randomness, thereby ensuring complete statistical transparency.

At Filter Stage F1

Turbidity vs. Salinity (r = 1.000, p undefined):

This positive correlation is perfect to show that the main contributor to the measurement of both turbidity and salinity in F1 effluent is due to the suspended particles that carry ionic species. With the removal of particles by means of filtration, the turbidity and electrical conductivity (calculation of salinity) decrease in the same proportion. This association confirms turbidity as a quick surrogate factor for ionic strength during filtration, allowing real-time monitoring of the process without laboratory testing. pH vs. Mg^{2+} (r = 1.000, p undefined): Excellent positive correlation is a confirmation that Magnesium loss is wholly dependent on pH. When Magnesium is at slightly elevated pH (7.61 ± 0.012 at F1), the Magnesium Hydroxide [$Mg(OH)_2$] co-precipitates with Calcium Carbonate. The equilibrium is based on a reduction in the solubility of Mg^{2+} as the pH rises: $Mg^{2+} + 2OH^- \rightleftharpoons Mg(OH)_2(s)$ ($Ksp = 5.61 \times 10^{-12}$)

The practical implication of this ideal correlation is that the most important lever for Magnesium (and hence total hardness) removal is pH control. Adding Alkaline chemicals (e.g., NaOH, Ca $(OH)_2$) would increase the amount of Magnesium 2 precipitated, and acidic conditions would resolubilize precipitated Magnesium. pH vs. SO_4^{2-} (r = -1.000, p = 0.012): It is a perfect negative correlation, which means that the removal of sulfates is also pH-dependent, but in the opposite direction. With an increase in pH, the degree of sulfate precipitation reduces. This opposing relationship is indicative of opposing mechanisms: Low PH: Improved adsorption to protonated aluminum/iron oxide surfaces on sand surfaces. At Alkaline PH: Decreased adsorption because of deprotonation of the surface and electrostatic repulsion. The ideal negative relationship indicates that adsorption, but not precipitation, is responsible for sulfate removal at F1, since the precipitation of sulfate as Gypsum ($CaSO_4$) or ettringite would increase with pH. This mechanistic understanding shows that a marginally acidic environment would optimize sulfate elimination but is unfavorable to optimal hardness removal (which occurs at Alkaline pH). Finding a balance between these conflicting demands would involve pH optimization in accordance with water quality priorities.

BOD_5 vs. TDS (r = -1.000, p undefined): A negative correlation equal to one indicates an inverse relationship between organic and inorganic content. Biofilm metabolism and physical filtration of biofilm reduce the biodegradable organic matter (BOD_5) levels, leading to a short-term increase in dissolved inorganic solids (TDS). This pattern reflects: 1- Mineralization: Organic end products (CO_2, NH_4^+, PO_4^{3-}, SO_4^{2-}) are released through bacterial oxidation of organic matter, temporarily increasing TDS. 2- Ion leaching: The adsorption of organic matter to filter media replaces the ions that have been previously adsorbed, releasing them into solution and raising TSS. 3-Biofilm metabolism: Active biofilms store organic matter at the expense of inorganic metabolic waste products. The operational implication of this ideal negative correlation is that a transient increase in TDS should be anticipated during filter start-up or when under low rates of organic loading, and it is not a sign of treatment failure. TDS level subsides as the biofilms grow and the filter media come into equilibrium.

Ca^{2+} vs. Turbidity (r = 1.000, p undefined): The positive correlation is perfect, confirming the formation of particulate matter through Calcium precipitation to

cause turbidity. When Calcium is destroyed as Calcium Carbonate ($CaCO_3$) or Calcium Phosphate ($Ca_3(PO_4)_2$), it forms suspended microcrystals that can scatter light, which can be measured as turbidity. This correlation proves the removal order: 1- Ca^{2+} that is dissolved precipitates as solid particles. 2-Turbidity is caused by particulate Calcium compounds. 3-Sand filtration eliminates the Calcium-containing particles as well as the turbidity. The ideal correlation means that turbidity values can be used as a real-time surrogate to monitor the efficiency of Calcium removal, allowing immediate monitoring of the process without the need to use wet chemistry.

At Filter Stage F2

EC vs. pH (r = -1.000, p = 0.001): There is a perfect negative correlation between EC and pH (at F2 only, not F1), which means that the lower the pH, the higher the electrical conductivity. This relationship reflects: Proton contribution: Reduced PH indicates an increased concentration of $H^{+,}$ and this directly raises ionic strength and EC. Mineral dissolution: Mineral dissolution favors dissolution of Carbonate minerals in slightly acidic conditions, releasing Ca^{2+}, Mg^{2+}, and HCO3- ions, which increase EC. Carbonate keeps its equilibria constant, and changes in pH modify the relative proportions of CO_3^{2-}, HCO_3^-, and H2CO3, which affect the total ionic strength. The null hypothesis is that the second filter has attained chemical equilibrium with the Carbonate chemistry, and F1 is still dynamic in terms of ion exchange and leaching. This fact proves that F2 is balanced, with steady filtration activity. pH vs PO_4^{3-}-P (r= 1.000, p undefined): There is a perfect positive relation at F2, which implies Phosphate behavior that is pH dependent, but opposite to F1. At a slightly lower pH (7.59) of F2, Phosphate speciation is preferential to $H_2PO_4^-$ rather than HPO_4^{2-}, and this is less adsorbed to mineral surfaces. The ideal correlation implies that within the close pH range of F2 (7.59 ± 0.010), Phosphate removal is highly pH-sensitive, and slight pH variations have significant impacts on adsorption/precipitation equilibria.

Conclusion

In this paper, the usefulness of ablution water treatment using multi-stage filtration with low-cost materials in the city of Ramadi, Iraq, was demonstrated. The treatment system adopted for the Al-Adel Omar bin Abdul Aziz Mosque consisted of a single sequential four-stage treatment train, each comprised of two filters: first a sand/gravel filter, then an activated Carbon filter. All the factors measured showed very high reduction ($p<0.01$) in the system. The turbidity decreased 98.95 (152 NTU to 1.60 NTU), BOD_5 decreased 73.3% (42.50 to 11.35 $mg.L^{-1}$), and COD decreased ≥92.6% (68.00 $mg.L^{-1}$ to Limit of Detection (below analytical detection limit - <DL = 5.0 $mg.L^{-1}$). The Total Bacterial Count (TBC) decreased from an initial value of 556.00 ± 0.00 $CFU.mL^{-1}$ to 15.50 ± 1.10 $CFU.mL^{-1}$after the first stage (F1), and subsequently to 1.25 ± 0.00 CFU. mL^{-1} after the second stage (F2). Ultimately, the complete system treatment combined with the subsequent disinfection process reduced the final TBC to 0.63 ± 0.00 CFU. mL^{-1}, representing an overall cumulative removal efficiency of 99.89%. The treated water met Iraqi quality standards (Category A_1) for wastewater reuse; final factors fell within acceptable limits: Total Dissolved Solids (TDS) at 1145.80 $mg.L^{-1}$, Total Suspended Solids (TSS) at 15.80 $mg.L^{-1}$, pH at 7.59, 5-day Biochemical Oxygen Demand

(BOD_5) at 11.35 $mg.L^{-1}$, and Total Bacterial Count (TBC) at 63 $CFU.100\ mL^{-1}$.

The Chlorine residual in the treated water was measured at 1.42 mg. L^{-1}, which is slightly higher than the recommended value of 1.0 $mg.L^{-1}$ by FAO for direct reuse in agriculture, so an additional treatment step to remove the Chlorine (e.g., light aeration or addition of Sodium thiosulfate/ sulfite) is recommended before unrestricted agricultural use to protect soil microbial ecology and plant tissue.

The final turbidity was lower in the treatment pathway that included sand filtration (F1+F2) than in the complete four-stage treatment pathway (1.60 NTU), due to shedding of fine Carbon particulate matter from the GAC stages. In contrast, both BOD5 and COD were significantly higher for organic matter removal using sand filtration (21.40 $mg.L^{-1}$ and 36.10 $mg.L^{-1}$, respectively), compared to the complete system (11.35 $mg.L^{-1}$ for BOD_5 and < DL for COD). It also establishes that the activated Carbon stages (F3, F4) are necessary whenever the removal of organic matter and residual Chlorine are treatment goals; however, it indicates that turbidity control may be accomplished with the sand stages alone if there is no need to reduce the organic load. The use of low-cost materials supports the sustainability of this trend, with a plain design that does not require much technical skill and a high level of water-saving potential. With around 2000 liters per day treated in a single mosque, it would be possible to design this system for the 201 mosques in Ramadi to decrease municipal water use dramatically. The study offers an effective and practical model that can be applied to water-stressed Islamic nations for sustainable water management. It proves that ablution water is a valuable resource, not waste. The developed treatment regimens can be easily replicated in similar facilities across Iraq and the larger Islamic world to support national water security strategies. Future research could focus on long-term performance monitoring, maximizing filter media lifespan, and a detailed analysis of the costs and benefits of large-scale adoption. Furthermore, expanding the observation sample size to encompass longer seasonal periods in future studies will address the "lack of variance" limitations observed in short-term correlations, thereby shifting predictive models from deterministic thresholds to more comprehensive probabilistic (stochastic) frameworks.

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