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Treatability Study of Car Wash Wastewater Using Upgraded Physical Technique with Sustainable Flocculant

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Abstract: Grease, oil, hydrocarbon residues, heavy metals, and surfactants are all present in car wash wastewater (CWW), which all can have detrimental effects on the environment and human health. This study was designed to assess CWW treatment using an upgraded physical technique combined with a range of conventional and more sustainable coagulants. Physical treatment effectively lowered the oil and grease (O&G) and chemical oxygen demand (COD) of the CWW by 79 ± 15% and 97 ± 1.6%, respectively. Additional treatment was provided using chemical coagulation–flocculation–settling. In jar test studies, humic acid (HA) and alum were found to provide significantly higher turbidity removal, 79.2 ± 3.1% and 69.8 ± 8.0%, respectively, than anionic polyacrylamide (APA), 7.9 ± 5.6% under influent turbidity values from 89 to 1000 NTU. Overall physical/chemical treatment of CWW yielded 97.3 ± 0.8% COD removal, and 99.2 ± 0.4% O&G removal using HA and alum. Due to the numerous problems created when using synthetic coagulants, naturally occurring coagulants that have no impact on human health, such as HA, are highly desirable options. The findings of this study show that treating CWW provides several advantages for sustainable development, health and well-being, and raising public knowledge and support for water reuse.

Keywords: car wash wastewater; baffled basin; humic acid; anionic polyacrylamide; alum; sustainable coagulant; water reuse

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1. Introduction

The availability of water resources worldwide is dwindling, and as a result, 2.7 billion people will experience water scarcity by 2025 [1]. The car wash process uses a large amount of fresh water, consuming 150–600 L per car [2–4]. Car wash wastewater (CWW) can be extensively contaminated with sand and particles, oil and grease, surfactants, detergents, phosphates, and even hydrofluoric acid [5–7]. The direct discharge of CWW into sewerage may reduce the efficiency of sewage treatment operations [5] because of incompatible waste components, and, as a result, treating CWW is essential for preventing environmental contamination and reducing the negative impact of car washing [8].

Various integrated physical and chemical CWW treatment systems have been developed for the reuse of treated water [2,5]. A previous study utilized an aeration system as pretreatment for oil removal via floatation. The detention time of this pretreatment step was 90 min to achieve 96.3% O&G removal efficiency [9]. The aeration system had high O&G removal efficiency, but it consumed a lot of energy, and blockage of the air diffusers could easily occur resulting in high operation and maintenance costs.

Bhatti and Mahmood [9] examined an integrated treatment process for CWW that consisted of aeration followed by alum and waste hydrogen peroxide addition to oxidize most of the remaining COD. This integrated treatment process reduced O&G by up to 96%, COD by 93%, turbidity by 94%, and TDSs by 74% [9]. Based on coagulation–flocculation and a household activated carbon filter and water ozonator, Canales and Plata-Solano [10] evaluated the removal efficiency of a bench-scale CWW treatment system. Organic matter treatment efficiency was above 70%, and color and turbidity removal was over 90%.

Owing to the characteristics of CWW, high turbidity (128–1000 NTU) [11,12] and total suspended solids (4200–5800 mg/L) [9,13], researchers commonly consider coagulation an effective method for improving the quality of treated CWW [14]. There are various chemicals coagulants that can be considered for wastewater treatment, but the recent trend is to utilize natural coagulants because of their advantages of low cost and low impact on the environment, as well as providing efficient treatment performance [15]. Al-Gheethi and Mohamed [5] developed an integrated treatment system for CWW based on coagulation and flocculation using *Moringa oleifera* (a natural coagulant) or Ferrous Sulphate ($FeSO_4 \bullet 7H_2O$) as well as a natural filtration system. The authors concluded that *M. oleifera* was more effective than $FeSO_4 \bullet 7H_2O$ in the treatment of polluted car wash effluent. In other research, an algae was used as natural coagulant in a photo-bioreactor in combination with a dissolved air flotation system (DAF); it was efficient in the removal of COD and total suspended solids (TSSs) from primary treated wastewater [16].

This research was carried out to investigate the effectiveness of combining physical/chemical methods for treating CWW at the laboratory scale by using an upgraded physical treatment technique followed by coagulation–flocculation. In the coagulation–flocculation step, a comparison among three types of coagulants, humic acid (HA) as a natural coagulant as well as Alum and anionic polyacrylamide (APA) as chemical coagulants, was also carried out.

2. Materials and Methods

2.1. CWW Sample Collection

Eight effluent samples were collected from a car wash in Alexandria, Egypt, between October 2021 and March 2022. The samples were collected in 20 L plastic containers and transported to the Sanitary Engineering Department, Faculty of Engineering, Alexandria University's laboratory and stored at ≤ 4 °C prior to analysis. O&G, COD, total dissolved solids (TDSs), dissolved oxygen (DO), pH, salinity, and turbidity were all measured using standard methods described below [17]. The results of the eight CWW sampling events are presented in Table 1.

Table 1. Characteristics of replicate car wash wastewater samples.

Parameter	Mean ± 95%CI	Min–Max
pH (Units)	7.7 ± 0.3	6.9–8.2
TDS (mg/L)	2642 ± 2507	650–10,573
Salinity (mg/L)	679 ± 88.3	445–884
Turbidity (NTU)	1526 ± 348	840–2200
COD (mg/L)	42,255 ± 18,288	9040–90,400
Oil and grease (mg/L)	127,301 ± 88,618	5054–316,573

2.2. Materials

Humic acid (HA) was purchased from LOBA CHEMIE PVT. LTD. (Mumbai, India). anionic polyacrylamide (APA) and Alum were purchased from El-Gomhouria Pharmaceutical and Chemicals Co. (Alexandria, Egypt).

2.3. Experimental Design

The lab-scale physical/chemical treatment system evaluated in this study is shown in Figure 1. The system was evaluated in three phases. Phase 1 was used to evaluate the effectiveness of the baffle tank for pollutant removal under a pump flow of 370 mL/min. The baffle tank consisted of seven baffle plates with a total volume of 23.9 L (≈65 min hydraulic retention time) to encourage over and under flow of CWW to enhance O&G separation. This baffle tank was used to remove excess O&G that could interfere with the subsequent chemical treatment and is a significant improvement on the conventional baffled tank design from Egyptian code that consists of only three baffled plates and has significantly shorter retention time requirements [18]. The O&G was withdrawn using valves from the surface of the baffled tank as is common practice in oil–water separators. Pollutant removal efficiency results were determined in a series of eight replicate experiments carried out during this phase of the study.

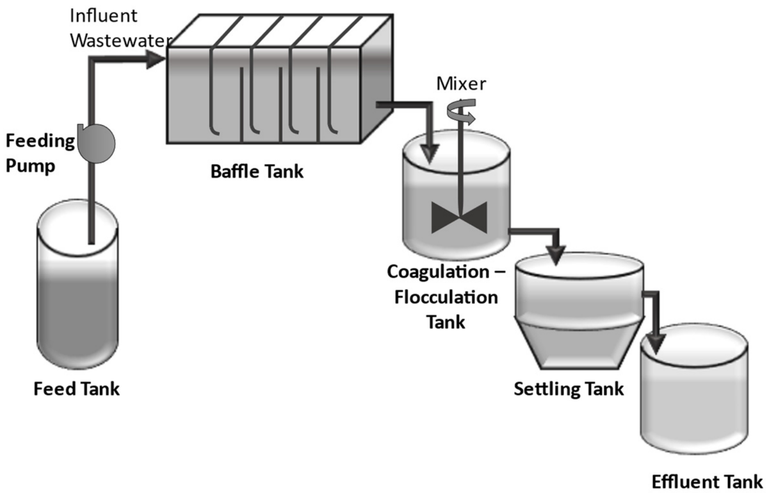

Figure 1. Schematic diagram of the experimental setup.

The second coagulation–flocculation phase was carried out using a standard jar test to select the optimum coagulant and coagulant dosages based on turbidity removal using the physically treated CWW, i.e., the baffle reactor effluent. Five different dosages of each coagulant, from 24 to 72 mg/L, were utilized in each batch of trials, along with a 0 mg/L dose blank. Six L of wastewater were collected from the baffle reactor effluent and were divided into 1 L beakers for each dose of each coagulant. After coagulant addition, rapid mixing was carried out for 2 min at 300 rpm followed by 20 min of gentle mixing at 50 rpm. The flocculated samples were then allowed to settle for 2 h prior to supernatant sampling for parameter analysis.

Phase 3 of the study evaluated the overall performance of the complete physical/chemical system, the baffled tank followed by coagulation–flocculation–sedimentation, as shown in Figure 1, using the coagulation–flocculation results from Phase 2. The sedimentation tank in this phase of the study was sized to provide a detention time of 2 hat operating flow rates. Triplicate runs using the entire treatment system were carried out at ambient temperature (20–25 °C).

2.4. Analytical Methods

The raw CWW and treated samples were analyzed using the following portable bench-top meters following the manufacturer's standard calibration and operating procedures: B30PCI Multimeter for pH, TDSs, electrical conductivity (EC), DO, and salinity. Turbidity was measured using an HI88703, HANNA instruments turbidimeter (Padova, Italy). COD was measured using the closed reflux, calorimetric method. Digestion was carried out at 150 °C for 2 h in COD vials followed by spectrophotometric readings at 530 nm. O&G was analyzed gravimetrically [17]. At least three readings were taken for each parameter in each instance, and a mean value was calculated and reported.

2.5. Statistical Analysis

StatPlus:mac version 8 (AnalystSoft Inc., Alexandria, VA, USA, AnalystSoft Inc.com) was used to carry out the statistical analysis of results collected in this study. Linear regression analysis of % turbidity removal as a function of initial turbidity values was carried out to determine if coagulant effectiveness was altered by initial water quality for each coagulant dose used in the Phase 2 jar test study. One-way analysis of variance (ANOVA) testing was used to determine significant differences among coagulants in pollutant removal in both jar test experiments, and results were observed for the complete physical/chemical treatment of CWW in Phase 3 of the study. A Box–Cox transformation was carried out to normalize the raw data prior to ANOVA testing. Significant regression relationships and significant differences among treatments were determined using an alpha value of 0.05, and post hoc analysis was carried out using Fisher's least significant difference (LSD) test.

3. Results and Discussion

3.1. Car Wash Wastewater Characteristics

As indicated in Table 1, wastewater characteristics were highly variable, especially for TDSs, COD, and O&G, ranging from one to two orders of magnitude in concentration, most likely owing to the highly variable types of vehicles being washed over the 6 month sampling period [19,20].

Researchers in [21–23] reported a wide pH range for CWW of 7 to 10. The pH values observed during this study, 7.0 to 8.6, were in line with observations of neutral to mildly alkaline CWW pH values reported by [22,24,25].

TSS and TDS concentrations of 3561 mg/L (905–4887 mg/L) and 1508 mg/L (728–2442 mg/L), respectively, were reported in CWW by Fall and Bâ [22]. TDS values observed in the CWW during this study were even higher, reaching nearly 11,000 mg/L in one of the samples collected for treatment. TSS measurements were not made, but measured turbidity values in the 1000 to 2000 NTU range are indicative of high levels of suspended materials expected in CWW prior to treatment.

Oil and grease concentrations in CWW were reported by Fall and Bâ [22] to be between 404 and 2876 mg/L, with an average value of 1099 mg/L. These reported values were greatly exceeded, by a factor of 10 to more than 300 in all CWW samples collected in this study. CWW contains shampoo, detergents, oils, fuels, etc., the materials that make CWW a turbid, high O&G, high COD solution [9].

Comparison of water quality values of the CWW used in this study (Table 1) to those reported in the literature indicate that while this CWW had similar pH characteristics, it was much higher in dissolved solids, and it was excessively high in O&G and dissolved organic matter, making it a much more complex and difficult-to-treat waste stream than would be typically expected from car wash facilities.

3.2. Phase 1: Results of CWW Treatment Using the Baffled Tank

Physical treatment of the CWW using the pilot-scale baffled tank was evaluated for each of the eight CWW sampling events carried out during the study to assess its performance characteristics under the widely varying water quality conditions observed in the field data. The baffled tank was particularly effective in the removal of COD and O&G as indicated in Table 2 despite the large variability in influent concentrations.

In a study using an aerobic bio filter (baffled septic tank) in which effluent flowed under a series of baffles, COD removal efficiency was found to range from 65–90% [26]. The baffled tank used in this study yielded a higher COD removal efficiency averaging 97% for CWW.

Table 2. Baffle tank physical treatment of CWW in Phase 1 pilot-scale studies.

Parameter	Influent (Mean ± 95%CI)	Effluent (Mean ± 95%CI)	% Removal (Mean ± 95%CI) *
pH (Units)	7.7 ± 0.3	7.8 ± 0.4	NSD
TDS (mg/L)	2642 ± 2507	721 ± 103	NSD
Salinity (mg/L)	679 ± 88.3	565 ± 84	NSD
Turbidity (NTU)	1526 ± 348	949 ± 484	NSD
COD (mg/L)	42,255 ± 18,288	717 ± 213	97 ± 1.6
Oil and grease (mg/L)	127,301 ± 88,618	30,886 ± 35,634	79 ± 15

* NSD indicates no significant difference between influent and effluent concentrations based on Fisher's LSD results.

Fall and Bâ [22] described an oil–water separator in underground tanks that they used to pretreat CWW before further processing it, as was performed with the above ground baffled tank in this study. Baffled oil–water separators are an efficient way to remove free and dispersed forms of oil if emulsified, and stable oil droplets can be destabilized before removal [27]. According to Paxéus [28], oil separator devices are not efficient in removing oil in the range of 10–1750 mg/L due to the formation of stable emulsions in the wastewater caused by detergents used in vehicle cleaning. The baffled tank used in this CWW treatment study was efficient in reducing the elevated concentration of influent O&G by an average of 79 ± 15%, but significant O&G and turbidity levels remained after physical treatment, so the CWW was ready for further reduction via the subsequent chemical treatment steps.

3.3. Phase 2: Coagulation–Flocculation Jar Test Results

Three coagulants were evaluated in jar test studies to assess CWW chemical treatment following physical treatment provided by the baffle tank. These coagulants included Humic acid (HA), anionic polyacrylamide (APA), and alum ($Al_2(SO_4)_3{\bullet}14H_2O$) at coagulant doses of 24, 30, 36, 48, and 72 mg/L. Each dose was added to 1 L of physically treated CWW from the baffle tank at five initial turbidity concentrations ranging from 89 to 1000 NTU; the samples in the jars were rapidly mixed for 2 min, flocculated for 20 min, and settled for 2 h prior to analysis of supernatant for final turbidity measurements. Figure 2 provides a summary of turbidity removal results for each coagulant tested in the study.

Using these turbidity removal results at each coagulant dose (Figure 2), linear regression analyses were carried out to determine if removal efficiency was affected by initial turbidity conditions. Table 3 summarizes these regression results, which indicate that despite generally positive relationships for turbidity removal as a function of increasing initial turbidity concentrations for alum and HA (Figure 2), these relationships were not significant at alpha value = 0.05. Results for APA generally showed decreasing turbidity removal with increasing initial turbidity values (Figure 2), but this negative relationship was only significant at an APA dose of 30 mg/L.

A Box–Cox transformation of turbidity removal results was carried out to normalize these removal efficiency values prior to conducting an ANOVA on the transformed data. Box–Cox transformation lambda values for each coagulant were 2, 2, and −0.54 for HA, alum, and APA, respectively. Once transformed, an ANOVA was run to evaluate significant differences in removal efficiency values at each coagulant dose. Both HA and APA did not show significant differences in removal efficiency as a function of dose; however, alum did display significantly higher turbidity removal efficiency at the 72 mg/L dose compared to the 24 and 30 mg/L doses based on a Fisher's least significant difference (LSD) result (p value ≤ 0.01).

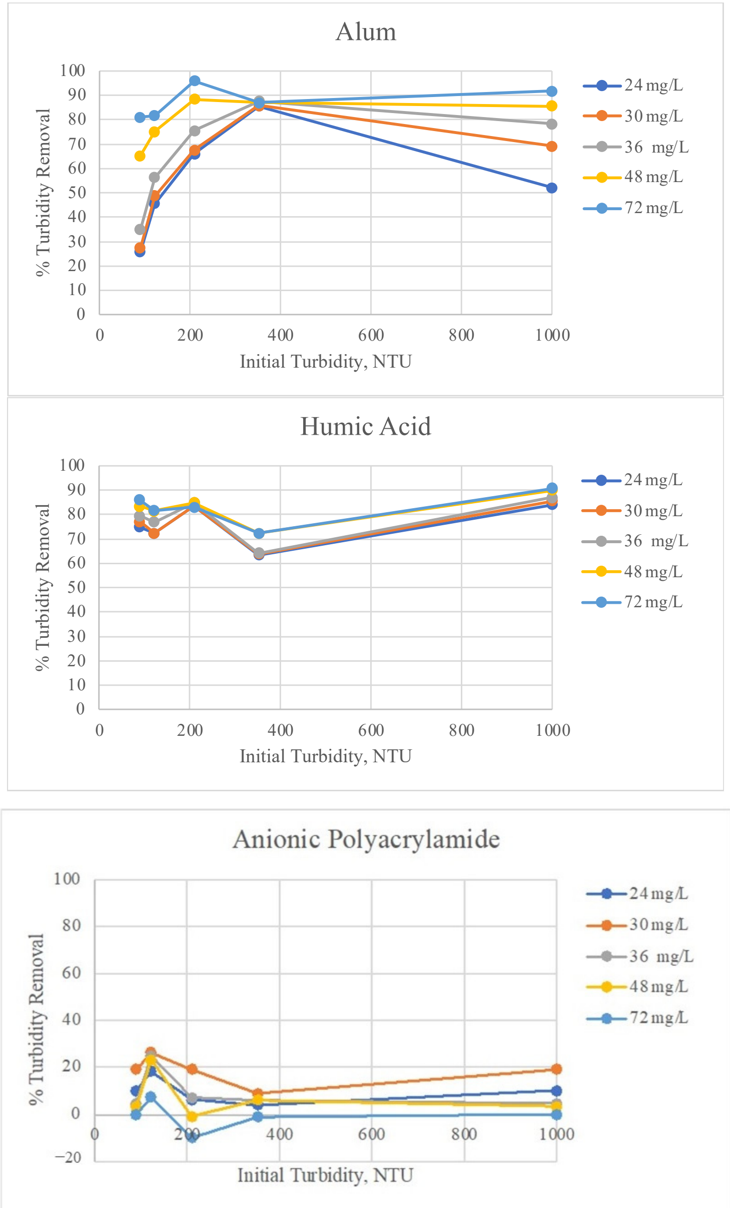

Figure 2. Percent turbidity removal results from Phase 2 jar test study of chemical treatment of physically treated CWW.

HA can be an adsorbent aid as well as a coagulant. Lower adsorption at lower doses may be caused by the adsorbate molecules saturating the surface-active sites of the coagulating solids. By increasing the HA concentration, the suspensions may have stayed dispersed because the repulsive forces acting on the HA surfaces were not appropriately neutralized [29]. This is consistent with this study's finding of no difference in turbidity removal among different HA doses.

In research using APA for removal of TSSs from agro-industrial wastewater, charge neutralization and sweep-floc mechanisms were both involved in particle aggregation [30]. These polymers created bridges between the particles and the polymer in addition to reducing the surface charge on the particles. Consequently, during the flocculation process, the bridged particles entangled with other spanned particles [31]. This outcome was linked to the strengthening of repelling interactions among the negatively charged particles limiting the effectiveness of this coagulant in agro-industrial wastewater [32] as was seen for CWW in this study.

Table 3. Percent turbidity removal versus initial turbidity regression results from Phase 2 jar test study of chemical treatment of physically treated CWW.

Coagulant Dose (mg/L)	Regression Results		
Alum	**Slope**	**R^2**	**Significant Regression**
24	0.0115	0.0372	No
30	0.0285	0.23	No
36	0.0303	0.2908	No
48	0.0132	0.2495	No
72	0.0083	0.2301	No
Humic Acid			
24	0.0093	0.1649	No
30	0.0101	0.186	No
36	0.0084	0.1252	No
48	0.0079	0.2171	No
72	0.0079	0.1945	No
Anionic Polyacrylamide			
24	−0.042	0.7397	No
30	−0.025	0.8175	Yes
36	−0.014	0.3164	No
48	−0.011	0.1755	No
72	−0.0005	0.0009	No

The transformed turbidity removal data were then combined across all coagulants to determine if significant differences existed in turbidity removal among coagulant type and dose. Results of this ANOVA indicated that both HA and alum provided significantly better turbidity removal than APA based on Fisher's LSD (p value $\leq$ 0.00001), and that HA was statistically better than alum at alum doses of 24 and 30 mg/L (Fisher's LSD p value < 0.002).

The lowest HA concentration achieved satisfactory turbidity removal (75.6%). The two intermediate HA doses (30 and 36 mg/L) were considered optimum for HA; however, it yielded a removal range of 76.5–78.5% at moderate chemical loadings. For alum, the lowest doses of 24 and 30 mg/L were found to produce statistically lower turbidity removal rates than the two highest doses used based on Fisher's LSD (p value < 0.001), while the intermediate dose (36 mg/L) was found to be statistically equivalent to the higher 48 mg/L dose used and was regarded as the optimum dose for alum. To carry out the evaluation of performance of the complete physical/chemical system in Phase 3, both HA and alum doses of 30 and 36 mg/L were incorporated into the complete system design, and these results are discussed in the next section.

3.4. Phase 3: Overall Physical/Chemical System Performance

The CWW was subjected to combined physical and chemical treatment (coagulation–flocculation–sedimentation) in the pilot-scale treatment system shown in Figure 1 using the two coagulants (HA and alum) at the two optimal coagulant doses determined in Phase 2 of the study. As in previous phases of the study, the baffle tank was operated with a hydraulic retention time of $\approx$ 65 min at a flow rate of 370 mL/min; the coagulation–flocculation units were run for 2 min at 300 rpm and 20 min at 50 rpm, respectively; and the sedimentation tank was operated with a hydraulic retention time of 2 h. Triplicate runs were conducted at each coagulant dose, and treated effluent was subjected to full characterization to determine the overall pollutant removal efficiency of the combined pilot treatment system. The results for the combined physical/chemical CWW treatment system are presented in Table 4 and are discussed in detail below.

Table 4. Combined physical/chemical treatment of CWW in Phase 3 pilot-scale studies.

Parameter	Influent (Mean ± 95%CI)	Effluent (Mean ± 95%CI)	% Removal (Mean ± 95%CI) *
Alum			
pH (Units)	7.9 ± 0.1		
30 mg/L		7.89 ± 0.2	NSD
36 mg/L		7.92 ± 0.2	NSD
TDS (mg/L)	5612 ± 5614		
30 mg/L		723 ± 232	NSD
36 mg/L		727 ± 230	NSD
Salinity (mg/L)	664 ± 248		
30 mg/L		560 ± 188	NSD
36 mg/L		564 ± 187	NSD
Turbidity (NTU)	1424 ± 536		
30 mg/L		180 ± 160	88.8 ± 9.3
36 mg/L		149 ± 111	90.4 ± 5.5
COD (mg/L)	22,600 ± 15,344		
30 mg/L		558 ± 267	97.2 ± 1.0
36 mg/L		589 ± 72	96.6 ± 2.4
Oil and grease (mg/L)	124,036 ± 190,425		
30 mg/L		518 ± 667	99.1 ± 0.9
36 mg/L		214 ± 146	99.2 ± 1.1
Humic Acid			
pH (Units)	7.9 ± 0.1		
30 mg/L		8.4 ± 0.3	—
36 mg/L		8.4 ± 0.3	—
TDS (mg/L)	5612 ± 5614		
30 mg/L		656 ± 110	NSD
36 mg/L		667 ± 129	NSD
Salinity (mg/L)	664 ± 248		
30 mg/L		558 ± 191	NSD
36 mg/L		562 ± 197	NSD
Turbidity (NTU)	1424 ± 536		
30 mg/L		222 ± 220	86.6 ± 11.2
36 mg/L		199 ± 231	88.1 ± 11.0
COD (mg/L)	22,600 ± 15,344		
30 mg/L		395 ± 48	97.6 ± 2.0
36 mg/L		404 ± 111	97.6 ± 1.9
Oil and grease (mg/L)	124,036 ± 190,425		
30 mg/L		475 ± 656	99.2 ± 0.8
36 mg/L		198 ± 161	99.5 ± 0.5

* NSD indicates no significant difference between influent and effluent concentrations based on Fisher's LSD results.

pH was slightly elevated in the effluent from the combined treatment system using HA as the coagulant compared to alum but remained within acceptable pH ranges that would not adversely impact receiving ecosystems. These findings are comparable to the results reported by Al-Gheethi and Mohamed [5] who evaluated the use of a range of natural coagulants for CWW treatment.

Although there were large fluctuations in influent COD, the combined system produced stable COD and O&G removal efficiency, largely due to effective pretreatment provided by the enhanced baffle tank design. As expected, removal efficiency for turbidity, COD, and O&G increased with the addition of chemical coagulation–flocculation–settling to the effluent of the baffled tank. In particular, both turbidity and O&G removal significantly increased with additional chemical treatment, likely due to the destabilization of oil emulsions and colloidal suspensions by both coagulants in the baffled tank effluent.

Average removal results shown in Table 4 were consistent for all pollutants across both coagulants and coagulant doses, and further statistical analysis of results was carried out parameter by parameter to determine if any significant differences did exist between the two coagulants evaluated in this pilot-scale treatment system.

The results of these statistical analyses are summarized in Table 5 and indicate that the only parameter showing a significant difference in removal efficiency based on the coagulant used was turbidity. Despite the high turbidity removal efficiency for both coagulants, once the data were Box–Cox transformed there was a significant difference in removal efficiency between them, with both HA doses yielding significantly lower removal efficiency than either alum dose based on Fisher's LSD results.

Table 5. Statistical results of pollutant removal for combined physical/chemical treatment of CWW in Phase 3 pilot-scale studies.

Parameter	Box–Cox Transformation Lamda Values		Statistical Difference—Fisher's LSD	*p*-Value for Significant Differences
	Alum	HA		
TDS (mg/L)	1.11	1.1	NSD	NA
Salinity (mg/L)	0.7	0.55	NSD	NA
Turbidity (NTU)	−2	−0.04	HA < alum	$<1 \times 10^{-4}$
COD (mg/L)	2	2	NSD	NA
Oil and grease (mg/L)	2	2	NSD	NA

Several studies of CWW treatment using coagulation [33] have investigated the effectiveness of natural coagulants such as HA. Wang [15] evaluated the effectiveness of *Moringa oleifera* and *Strychnos potatorum* as natural coagulants to effectively remove turbidity in CWW. These natural coagulants were found to offer a larger effective dose range for flocculation of different colloidal suspensions than conventional chemical coagulants, and they are biodegradable and safe for human health. The experiment revealed that *Strychnos Potatorum* performed better (>95% turbidity reduction) in turbid water than alum, ferrous sulfate, and *Moringa oliefera* [15].

Despite the very high removal rates achieved with the pilot treatment system, due to the very high CWW influent mean concentrations of turbidity (>1500 NTU), COD (>42,000 mg/L), and O&G (>127,000 mg/L), mean effluent concentrations of these parameters (150–220 NTU, 400–600 mg/L COD, 200 to 500 mg/L O&G) are generally considered higher than standard limits for most wastewater reuse or direct discharge applications. Additional treatment techniques can be utilized to improve the quality of the reclaimed CWW for direct reuse purposes including techniques such as nanofiltration and reverse osmosis [34] or ultrafiltration-activated carbon adsorption [35]. Many of these options would be expensive in terms of both capital and operation and maintenance costs, have a large footprint, and/or are inefficient [36]. Direct discharge to a municipal wastewater treatment plant after pretreatment using the combined CWW treatment system described in this study would be expected to be the most cost effective and environmentally responsible option for CWW.

4. Conclusions

The public's increased concern over water conservation, the safety and health of the public water supply, and environmental health have prompted the creation of environmental regulatory frameworks to safeguard watersheds and drinking water. Car washes utilize significant quantities of water and discharge wastewater that may contain harmful chemicals into the environment. The characteristics of CWW discharge are significantly influenced by the type and quantity of cleaning solutions and finishing chemicals used, the solid particles washed from vehicles, and the level of treatment applied to the CWW before discharge. In this study, an integrated treatment process, consisting of an improved physical separation baffle tank followed by chemical coagulation–flocculation and sedimentation, was designed and tested for its ability to provide consistent and effective pollutant removal from CWW. High removal efficiencies for turbidity (>86%), COD (> 96%), and O&G (>99%) were provided by the integrated treatment system, with alum providing slightly higher removal efficiency than HA only for turbidity at the optimal coagulant doses determined using laboratory jar testing.

While further treatment of effluent from this pilot physical/chemical treatment process would be necessary for most direct reuse options, the system as designed and tested is a cost-effective approach for reducing CWW pollutant loads and shock discharges to a wastewater treatment plant and sewage system. The system can be implemented using a small footprint without pH control and was shown to be highly effective with the use of HA as a coagulant. As indicated above, HA has many benefits over conventional chemical coagulants, being a natural product that is low-cost, safe to produce and use, and environmentally benign. With the recommendation of HA as the coagulant of choice, this integrated physical/chemical treatment system represents an effective, sustainable option for CWW treatment to improve health and well-being and raise public knowledge of and support for wastewater treatment and water reuse.

Author Contributions: All authors contributed to the study's conception and design. They performed material preparation, data collection, and analysis. M.F. (Mai Fayed) designed and employed the treatment system, interpreted the data, and wrote the manuscript. Additionally, she proofread and approved the final manuscript. M.A.S. assisted in the treatment system employment. She also assisted in revising the manuscript critically. R.R.D. analyzed and interpreted the data and proofread and approved the final manuscript. M.F. (Mohamed Fayed) interpreted the data and wrote the manuscript. M.M.B. performed the physicochemical analysis of water samples along with the whole system, analyzed and interpreted the data, and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

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

Abbreviations

$Al_2(SO_4)_3 \bullet 14H_2O$	Alum
ANOVA	Analysis of variance
APA	Anionic polyacrylamide
CI	Confidence interval
COD	Chemical oxygen demand
CWW	Car wash wastewater
DAF	Dissolved air floatation
DO	Dissolved oxygen
EC	Electrical conductivity

$FeSO_4 \bullet 7H_2O$	Ferrous Sulfate
HA	Humic acid
LSD	Least significance difference
NSD	No significant difference
O&G	Oil and grease
TDSs	Total dissolved solids
TSSs	Total suspended solids

References

1. Morel, A. *Greywater Management in Low and Middle-Income Countries*; Swiss Federal Institute of Aquatic Science and Technology: Dubenforf, Switzerland, 2006.
2. Durna, E.; Genç, D. Application of a multiple criteria analysis for the selection of appropriate radical based processes in treatment of car wash wastewater. *Environ. Eng. Res.* **2020**, *26*, 200115. [CrossRef]
3. Gönder, Z.B.; Balcıoğlu, G.; Vergili, I.; Kaya, Y. Electrochemical treatment of carwash wastewater using Fe and Al electrode: Techno-economic analysis and sludge characterization. *J. Environ. Manag.* **2017**, *200*, 380–390. [CrossRef] [PubMed]
4. Lau, W.J.; Ismail, A.F.; Firdaus, S. Car wash industry in Malaysia: Treatment of car wash effluent using ultrafiltration and nanofiltration membranes. *Sep. Purif. Technol.* **2013**, *104*, 26–31. [CrossRef]
5. Al-Gheethi, A.A.; Mohamed, R.M.S.R.; A A Rahman, M.; Johari, M.R.; Kassim, A.H.M. Treatment of Wastewater From Car Washes Using Natural Coagulation and Filtration System. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *136*, 012046. [CrossRef]
6. Soczka Mandac, R.; Bogunović, B.; Žagar, D.; Faganeli, J. Riverine impact on the thermohaline properties, turbidity and suspended solids in a shallow bay (Bay of Koper, northern Adriatic Sea). *Acta Adriat. Int. J. Mar. Sci.* **2014**, *55*, 195–212.
7. Zaneti, R.; Etchepare, R.; Rubio, J. More environmentally friendly vehicle washes: Water reclamation. *J. Clean. Prod.* **2012**, *37*, 115–124. [CrossRef]
8. Ghaly, A.E.; Mahmoud, N.S.; Ibrahim, M.M.; Mostafa, E.A.; Abdelrahman, E.N.; Emam, R.H.; Kassem, M.A.; Hatem, M.H. Carwash Wastewater Treatment and Reclamation Technologies for Water Conservation and Pollution Load Reduction: A Review. *Int. J. Biopro. Biotechnol. Adv.* **2021**, *7*, 274–310.
9. Bhatti, Z.A.; Mahmood, Q.; Raja, I.A.; Malik, A.H.; Khan, M.S.; Wu, D. Chemical oxidation of carwash industry wastewater as an effort to decrease water pollution. *Phys. Chem. Earth, Parts A/B/C* **2011**, *36*, 465–469. [CrossRef]
10. Canales, F.A.; Plata-Solano, D.; Cantero-Rodelo, R.; Pereira, Y.; Díaz-Martínez, K.; Carpintero, J.; Kaźmierczak, B.; Tavera-Quiroz, H. Assessment of carwash wastewater reclamation potential based on household water treatment technologies. *Water Resour. Ind.* **2021**, *26*, 100164. [CrossRef]
11. El-Ashtoukhy, E.-S.Z.; Amin, N.K.; Fouad, Y. Treatment of real wastewater produced from Mobil car wash station using electrocoagulation technique. *Environ. Monit. Assess.* **2015**, *187*, 1–11. [CrossRef]
12. Moazzem, S.; Wills, J.; Fan, L.; Roddick, F.; Jegatheesan, V. Performance of ceramic ultrafiltration and reverse osmosis membranes in treating car wash wastewater for reuse. *Environ. Sci. Pollut. Res.* **2018**, *25*, 8654–8668. [CrossRef] [PubMed]
13. Boluarte, I.A.R.; Andersen, M.; Pramanik, B.K.; Chang, C.-Y.; Bagshaw, S.; Farago, L.; Jegatheesan, V.; Shu, L. Reuse of car wash wastewater by chemical coagulation and membrane bioreactor treatment processes. *Int. Biodeterior. Biodegrad.* **2016**, *113*, 44–48. [CrossRef]
14. Medel, A.; Ramírez, J.A.; Cárdenas, J.; Sirés, I.; Meas, Y. Evaluating the electrochemical and photoelectrochemical production of hydroxyl radical during electrocoagulation process. *Sep. Purif. Technol.* **2019**, *208*, 59–67. [CrossRef]
15. Wang, Y. Moringa Oleifera and Strychnos Potatorum Seeds as Natural Coagulant Compared with Synthetic Common Coagulants in Treating Car Wash Wastewater: Case Study. *Am. J. Appl. Sci.* **2020**, *11*, 1–6.
16. Badawi, A.K.; Ismail, B.; Baaloudj, O.; Abdalla, K.Z. Advanced wastewater treatment process using algal photo-bioreactor associated with dissolved-air flotation system: A pilot-scale demonstration. *J. Water Process. Eng.* **2022**, *46*. [CrossRef]
17. Rice, E.W.; Bridgewater, L. *Standard Methods for the Examination of Water and Wastewater*; American Public Health Association: Washington, DC, USA, 2012; Volume 10.
18. Ministry of Housing Utilities and the Urban Development. *Egyptian Code for Design and Implementation Requirement for Engineering of Sanitary Structure of Buildings*; Code 301; Centre for Housing and Construction Research: Cairo, Egypt, 2013; Volume 1.
19. Kashi, G.; Younesi, S.; Heidary, A.; Akbarishahabi, Z.; Kavianpour, B.; Kalantary, R.R. Carwash wastewater treatment using the chemical processes. *Water Sci. Technol.* **2021**, *84*, 16–26. [CrossRef]
20. Magnago, R.F.; Berselli, D.; Medeiros, P. Treatment of wastewater from car wash by fenton and photo-fenton oxidative processes. *J. Eng. Sci. Technol.* **2018**, *13*, 838–850.
21. Gorsuch, A.M.; Denit, J.; Stigall, C.E.; Martin, E.E. Guidance document for effluent discharges from the auto and other laundries point source category. In *Effluent Guidelines Division*; Office of Water and Wastewater Management, United States Environmental Protection Agency: Washington, DC, USA, 1982; Volume 11, p. 2020.
22. Fall, C.; Bâ, K.M.; Jiménez-Moleon, M.C.; García-Pulido, D.; López-Vázquez, C.M.; Lucero-Chavez, M.; Díaz-Delgado, C. Carwash wastewaters: Characteristics, volumes, and treatability by gravity oil separation. *Rev. Mex. De Ing. Química* **2007**, *6*, 175–184.
23. Nguegang, B.; Sibanda, T.; Tekere, M. Cultivable bacterial diversity, physicochemical profiles, and toxicity determination of car wash effluents. *Environ. Monit. Assess.* **2019**, *191*, 478. [CrossRef]

24. Sibanda, T.; Selvarajan, R.; Tekere, M. Targeted 16S rRNA amplicon analysis reveals the diversity of bacterial communities in carwash effluents. *Int. Microbiol.* **2018**, *22*, 181–189. [CrossRef]
25. Monney, I.; Donkor, E.A.; Buamah, R. Clean vehicles, polluted waters: Empirical estimates of water consumption and pollution loads of the carwash industry. *Heliyon* **2020**, *6*, e03952. [CrossRef] [PubMed]
26. Foxon, K.M.; Pillay, S.; Lalbahadur, T.; Rodda, N.; Holder, F.; Buckley, C.A. The anaerobic baffled reactor (ABR): An appropriate technology for on-site sanitation. *Water SA* **2005**, *30*, 44–50. [CrossRef]
27. da Rosa, J.J.; Rubio, J. The FF (flocculation–flotation) process. *Miner. Eng.* **2005**, *18*, 701–707. [CrossRef]
28. Paxéus, N. Vehicle washing as a source of organic pollutants in municipal wastewater. *Water Sci. Technol.* **1996**, *33*, 1–8. [CrossRef]
29. Coles, C.A.; Yong, R.N. Humic Acid Properties and Implications for Treatment of Wastewater Containing Metals. In *Geo-Environmental Engineering: Integrated Management of Groundwater and Contaminated Land*; Yong, R.N., Thomas, H.R., Eds.; ICE Publishing: London, UK; Thomas Telford Ltd.: London, UK, 2004; pp. 29–36. [CrossRef]
30. Teh, C.Y.; Wu, T.Y.; Juan, J.C. Optimization of agro-industrial wastewater treatment using unmodified rice starch as a natural coagulant. *Ind. Crop. Prod.* **2014**, *56*, 17–26. [CrossRef]
31. Metcalf, L.; Eddy, H.P.; Tchobanoglous, G. *Wastewater Engineering: Treatment, Disposal, and Reuse*, 4th ed.; McGraw-Hill: New York, NY, USA, 2003; Volume 4.
32. Zinatizadeh, A.A.; Ibrahim, S.; Aghamohammadi, N.; Mohamed, A.R.; Zangeneh, H.; Mohammadi, P. Polyacrylamide-induced coagulation process removing suspended solids from palm oil mill effluent. *Sep. Sci. Technol.* **2017**, *52*, 520–527. [CrossRef]
33. Ali, E.N.; Muyibi, S.A.; Salleh, H.M.; Salleh, M.R.; Alam, M. Moringa oleifera seeds as natural coagulant for water treatment. In Proceedings of the Thirteenth International Egyptian Water Technology Conference, Hughada, Egypt, 12–15 March 2009.
34. Brown, C. Water use in the professional carwash industry. In *A Report for the International Carwash Association*; International Carwash Association, Inc.: London, UK, 2002.
35. Hamada, T.; Miyazaki, Y. Reuse of carwash water with a cellulose acetate ultrafiltration membrane aided by flocculation and activated carbon treatments. *Desalination* **2004**, *169*, 257–267. [CrossRef]
36. Zaneti, R.; Etchepare, R.; Rubio, J. Car wash wastewater reclamation. Full-scale application and upcoming features. *Resour. Conserv. Recycl.* **2011**, *55*, 953–959. [CrossRef]