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Assessment of carwash wastewater reclamation potential based on household water treatment technologies

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A R T I C L E I N F O

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A B S T R A C T

This paper assesses a bench-scale carwash wastewater treatment system's removal efficiency based on coagulation-flocculation and a household-type activated carbon filter and water ozonator. For the experiment, the wastewater that went through an oil/water separator (OWS) from a medium-sized carwash facility located in a dense commercial area in Barranquilla, Colombia, was collected. The study evaluates the following parameters: water quality indicators recommended by the U.S. Environmental Protection Agency and literature related to carwash water reclamation. The treatment results are compared to related regional studies in Latin America and Colombian legislation in force. Experimental results evidence that reclaimed water's characteristics are similar to those of a groundwater source for most analyzed variables, and the system was able to reduce organic matter concentrations considerably. Regarding the organoleptic characteristics, the system eliminated foaming and generated a transparent and odorless product. The coliform test showed that reclaimed water has an average total coliform count of around 5800 MPN/100 ml, which is above the proposed health risk limit per most international standards for water reuse; but as it complies with industrial wastewater and non-food irrigation purposes in Colombia, additional disinfection is recommended depending on the reuse purpose. The results from this research may assist future carwash wastewater reclamation regulations in Colombia and the Latin American region.

1. Introduction

The effects of climate change, coupled with the increasing human population and its living standards, have a significant impact on water availability and quality, as they aggravate the unequal distribution of this resource worldwide [1]. The challenges posed by water scarcity and increasing demands lead many countries to consider water reuse, as the sustainable development of cities critically

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depends on water availability [2,3]. Water reclamation, used synonymously with water recycling, is the process of treating wastewater to enable its reuse by satisfying fit-for-purpose water quality criteria [4].

Around 80% of the total wastewater of the world is released directly to the environment without any treatment [5]. By the beginning of the century, the estimated wastewater reuse volume was less than 1% of the world's total water withdrawal [6]. Currently, and led by China, Israel, and some European countries, around 5% of the global treated wastewater is reused in agriculture and for industrial applications [7]. Wastewater reclamation and reuse increase water supplies and might help reduce the pressure on aquifers and freshwater sources. According to Ref. [8]; the cost of recycled water can be as low as US\$0.32/m^3 for agricultural and industrial purposes, and US\$0.45/m^3 for potable water, which in some cases is cheaper than desalination (US\$0.50/m^3 on average) or than exploiting new water bodies or depleting existing resources. Recent studies have proven that most consumers are willing to pay and use reclaimed water only if the price is lower than that of conventional water [9,10]. Besides the economic aspect, and based on surveys conducted in the United States over two decades, other factors affecting the public acceptance of reclaimed water include the degree of human contact, health risks, clear definition of environmental and water conservation benefits, high-quality standards of the product, and confidence in the authorities and technologies involved [11].

The most common uses for recycled wastewater include irrigation [12–15], non-drinkable household uses [16–18], environmental management and recreational uses [19–23], aquifer recharge [24,25], aquaculture [26,27], drinking water production [9,28], and industrial applications [29–31]. According to the review paper by Ref. [32]; non-potable reuse is the most common usage for reclaimed water in small, medium, and large-scale applications.

In most developing countries, wastewater reclamation is not a common practice yet; however, many countries have made efforts in this direction by setting regulations encouraging water reuse following global trends around environmental protection and circular economy [33,34]. Carwashing is one of the regular daily-life activities that consume large water volumes, thus justifying efforts for reducing its impact on natural resources [35,36]. Wastewater from this process might include several pollutants, including detergents, high oil and grease concentrations, fuel residues, metals, salts, and organic matter [37].

Based on a sample of 3657 regular vehicles in Ghana [38], determined that the average water consumption in the carwash process ranges within 70 L (for motorbikes) and 365 L (for buses and vans), with manual washing stations consuming between 30% and 50% more water than semi-automated stations. For a family car, home carwashing consumes around 440 L of water [30]. Coupled with such a high level of water consumption, the carwash industry in low-income countries usually extracts unmetered groundwater for free and releases polluted wastewater into sewer systems and urban waterways. Negative consequences of such behavior include uncontrolled depletion of aquifers and potential pollution of soil and water bodies [38].

Therefore, industry-specific legislation is often required to minimize these risks, along with water-saving initiatives and practices. Examples from Australia and some European countries show that it is possible to limit the maximum freshwater carwash consumption to less than 70 L per an average car or achieve a water recycling percentage of up to 80%, observing significant revenue increases at the same time [4,38]. There are many industrial water recycling systems developed for potable and non-potable uses. The review paper by Ref. [39] summarizes leading water treatment technologies producing recycled water of various qualities and varying range of technical and energy requirements. For the carwash industry, the most common technologies are coagulation/adsorption, membrane filtration, electrochemical processes, and methods that combine multiple technologies [40]. Besides studies aiming at maximizing water recycling, water-saving initiatives in the carwash industry include the efforts to achieve an optimal design of pipe nozzles and control devices for automated systems [41].

Several household water treatment technologies have been developed to improve drinking water quality and its organoleptic characteristics, with different degrees of effectiveness in removing contaminants [42]. Among these technologies, two are of particular interest for this research: activated carbon filters and ozonation, as they are widely available and often locally produced even in low-income countries.

Activated carbon filters are commonly employed in water and wastewater treatment, both for households and industries, as they can treat general taste and odor problems and remove impurities such as certain organic compounds and heavy metals [43]. These devices enhance water quality through physical filtration, as the porous structure of the carbonaceous material adsorbs most of the pollutants in the water flow. Nevertheless, activated carbon filters are unsuitable for removing microbial contaminants, and both the U.S. Environmental Protection Agency (U.S. EPA) and the World Health Organization recommend using additional treatment to reduce microbial risks [44].

In use since the late 1800s, ozonation is a water treatment process with an efficient microbicidal effect against bacteria, viruses, and protozoan [45]. Ozonation oxidizes micropollutants through a direct reaction with highly reactive ozone molecules or indirectly, through hydroxyl radicals. Therefore, the transformation of compounds usually results only in their partial removal from the effluent [46]. Since the early 2000s, it has been the subject of research related to the carwash industry wastewater treatment. The findings of many reports indicate that ozonation performs better than chlorination in clarifying water while having an additional advantage: it does not leave undesirable odors, nor does it generate carcinogenic compounds called trihalomethanes [4,47].

This study evaluates a bench-scale carwash wastewater treatment system's pollutant removal efficiency based on coagulation-flocculation, activated carbon, and water ozonation technologies. The analyzed arrangement comprises equipment commonly employed for household water treatment and purification. This paper contributes to the literature on wastewater treatment and reclamation by assessing economic and already available alternatives, which is especially relevant for developing countries, where environmental legislation gaps, limited access to state of the art technologies, and inadequate local technical training are frequent, constituting a combination that poses a risk to sustainability and future access to water resources. Additionally, the reclaimed water characteristics from this work are compared with the existing Colombian legislation related to water for human consumption, wastewater disposal, and reuse.

Table 1
Carwash wastewater and reclaimed water characteristics from studies conducted in Latin America.

Authors:	[48]			[49]			[50]			[51]			[52]		
Country:	Brazil			Brazil			Mexico			Venezuela			Brazil		
Technology employed	Flocculation-column flotation (FCF) + Sand filtration + Chlorination			Flocculation–flotation + Ozonation			Electrocoagulation + Electrooxidation			Coagulation-Flocculation-Sedimentation			Rotating Biological Contactor + Filtration + Chlorination		
PARAMETER [UOM]	WW	RW	**Δ**	WW	RW	**Δ**	WW	RW	**Δ**	WW	RW	**Δ**	WW	RW	**Δ**
pH [−]	7.40	7.30	**−1.4%**	6.40	7.30	**14.1%**	7.30	8.33	**14.1%**	7.59	6.89	**−9.2%**	6.10	6.00	**−1.6%**
Conductivity [mS/cm]	0.47	0.57	**22.0%**	0.93	1.07	**14.5%**	0.80	0.71	**−10.6%**				0.60	0.59	**−1.7%**
TDS [mg/L]	345	387	**12.2%**	700	686	**−2.0%**							284	277	**−2.5%**
COD [mg/L]	191	71	**−62.8%**	683	96	**−85.9%**	488	55	**−88.7%**	264	7	**−97.5%**	626	296	**−52.7%**
Color [PCU]							4200	30	**−99.3%**	325	5	**−98.5%**	242	51	**−78.9%**
Turbidity [NTU]	103	9	**−91.3%**	229	10	**−95.6%**	898	14	**−98.4%**	208	2	**−99.2%**	156	28	**−82.1%**
BOD_5^{20} [mg/L]	68	27	**−60.3%**	397	61	**−84.8%**	151	11	**−93.0%**				169	24	**−85.8%**
Total Coliforms [MPN-CFU/100 ml]	4.7E+05	2.1E+04	**−95.5%**	5.3E+06	3.6E+04	**−99.3%**									
Oil and Grease [mg/L]	11.00	8.00	**−27.3%**				368.82	0.00	**−100.0%**						

Over the last ten years, studies conducted in Latin America around carwash wastewater recycling have combined different treatment technologies, including Flocculation-column flotation (FCF) + Sand filtration + Chlorination [48], Flocculation–flotation + Ozonation [49], Electrocoagulation + Electrooxidation [50], Coagulation-Flocculation- Sedimentation [51], and Rotating Biological Contactor + Filtration + Chlorination [52]. The wastewater and reclaimed water characteristics reported in these papers are summarized in Table 1, enabling a comparison with the results of this research, especially in developing countries such as those of the Latin American region.

2. Materials and method

2.1. Evaluated parameters

The pollutants found in carwash wastewater originate mainly from road surface contaminants, atmospheric fallout, combustion-derived contaminants, and carwash chemicals [53]. The parameters evaluated in this study are in line with U.S. EPA Guidelines (the [54] and existing literature regarding carwash wastewater treatment [4,30,48,49]. Table 2 presents the parameters under analysis and the examination methods [55] as well as equipment employed for conducting the task.

2.2. Case study and sampling

This study employed wastewater collected from a 450 m^2 carwash facility located in a dense commercial area in Barranquilla (Colombia) to test the described system. The carwash does not include any automatic equipment. The city's growth and the abundance of groundwater resources have stimulated the propagation of this type of economic activity. These features, coupled with legislative shortcomings and limited supervision from the authorities, produce negative externalities with environmental impacts, such as health and safety concerns caused by untreated effluent being discharged directly to the streets, uncontrolled depletion of aquifers, and squandering of local water resources [30,56,57,79].

The samples were collected based on the procedures described in Standard Methods for the Examination of Water and Wastewater. Between July and September 2019, thirteen batches of at least 40-liter wastewater units were gathered, with the corresponding experimental run and analysis of the parameters under evaluation conducted within 24-h of collection. For each experimental run, three samples were collected and tested at each sampling point: 1) downstream the oil/water separator (OWS) in the carwash facility; 2) after the coagulation-flocculation process; 3) from the ozonator. The tests related to total coliforms and oil and grease concentration were conducted only for three experimental runs because of logistical difficulties.

2.3. The wastewater treatment system

The system's main components include technologies commonly available for household applications, and Fig. 1 shows the schematic representation of the carwash wastewater treatment system under study, with the process described in the following subsections. The capital cost of the equipment used in this bench-scale experiment (grease trap, tanks, filters, pipe fittings, pump, and ozonator) was about US$900, with the sum of the ozonator and the activated carbon filter accounting for 40% of the total.

2.3.1. Wastewater batch collection

At the carwash facility, a pump directly draws groundwater from a borehole, storing the resource in an elevated tank to meet the business's operational requirements. Wastewater derived from the carwashing process (pre-soak, wash, and rinse) is collected by an in-bay-pit, which serves as a desander and coarse material separator. Following the pit, the carwash employed as the case study currently disposes wastewater directly to the city sewage system. Water extracted from the in-bay-pit is passed through a 95-liter polyethylene OWS to reduce the equipment's clogging risk. Each experimental run requires a minimum of 40-liters of wastewater to be treated by the system, and the batches are collected downstream of the OWS, which is also the first sampling point. These volumes are taken

Table 2
Parameters under analysis and examination methods or equipment employed.

Parameter	Units of measurement	Examination method/Equipment
pH	–	EcoSense® pH100A
Dissolved Oxygen (DO)	ppm	EcoSense® DO200A
Electrical Conductivity (EC)	mS/cm	EcoSense® EC300A
Salinity	ppt	EcoSense® EC300A
Total Dissolved Solids (TDS)	mg/L	EcoSense® EC300A
Chemical Oxygen Demand (COD)	mg/L	5520 D
Color	PCU	I727 Checker® Handheld Colorimeter
Turbidity	NTU	Hach 2100Q Turbidimeter
Alkalinity	mg $CaCO_3$/L	2320 B
Biochemical Oxygen Demand (BOD_5^{20})	mg/L	5210 B
Total coliforms	MPN/100 mL	9221 B
Oil and grease	mg/L	5520 D

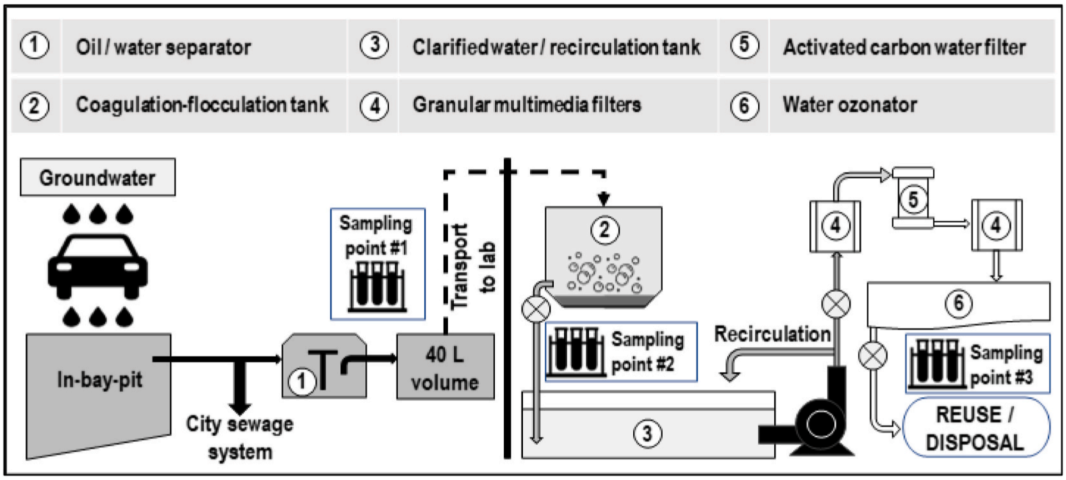

Fig. 1. Schematic of the carwash wastewater treatment system.

directly to the laboratory of the Universidad de la Costa for the treatment process to be continued.

2.3.2. *Coagulation-flocculation process*

For the system's 40 L coagulation-flocculation tank, two airstone bubblers replicate gentle mixing conducted in the jar test. This aerator type is extensively used in house aquariums, and for the experiment, the bubblers were set 10 cm above the tank's bottom, allowing for sedimentation to occur. The jar tests followed the procedures described by the Colombian Institute of Technical Standards and Certification [58], which constitute an equivalent to the practices described in ASTM D 2035-90. Based on previous research [51, 59], the 1% ferric chloride ($FeCl_3$) solution was chosen as the coagulant for this experiment. It is worth mentioning that $FeCl_3$ is highly corrosive; thus, reclaimed water should be avoided for the final rinse [52,60]. Ten possible dosages within the range of 20 mg/L and 120 mg/L (mg of $FeCl_3$ per liter of wastewater) were tested on nine preliminary wastewater samples from the site before the actual experimental runs were conducted. From these analyses, an initial dose of 90 mg/L allowed for the best clarification conditions for the combined assessment of pH, absorbancy, color, and alkalinity. Once the operation was complete and the flocs settled, the clarified water (second sampling point) was passed on to another tank, and the sediments from the coagulation-flocculation process were safely discarded.

2.3.3. *Activated carbon and ozonation*

Besides the OWS and the coagulation-flocculation tank, the system's configuration comprises two additional household water treatment devices: an activated water carbon filter (flow rate capacity: 4 L/min) and a water ozonator (nominal power: 12 W; flow rate capacity: 2 L/min). Research related to utility-scale wastewater treatment plants has previously evaluated this technology combination [61,62]. The system analyzed in this paper includes granular multimedia filters installed in both devices to extend these pieces of equipment's service life. A ½ HP pump (flow rate: 40 L) circulates water from the clarified water/recirculation tank to the rest of the system. The ozonator's flow rate determines the system's output, resulting in an estimated residence time of 20 min for a 40-liter

Table 3
Characterization of wastewater at each sampling point. Abbreviatures: n: Number of samples, Avg: Average, SD: Standard Deviation, GW: Groundwater, OWS: Downstream the oil/water separator, CF: After completing coagulation-flocculation, RW: Reclaimed water.

PARAMETER [units]	GW (n = 9)		OWS (n = 48)		CF (n = 39)		RW (n = 39)		$\Delta = \frac{\overline{RW} - \overline{OWS}}{\overline{OWS}}$
	Avg	*SD*	Avg	*SD*	Avg	*SD*	Avg	*SD*	
pH [−]	**7.736**	*0.086*	**7.584**	*0.271*	**7.144**	*0.235*	**7.222**	*0.133*	−4.8%
DO [ppm]	**4.744**	*0.241*	**2.271**	*1.209*	**4.119**	*0.804*	**4.022**	*0.598*	77.1%
Conductivity [mS/cm]	**0.715**	*0.005*	**0.835**	*0.064*	**0.890**	*0.081*	**0.829**	*0.165*	−0.7%
Salinity [ppt]	**0.356**	*0.053*	**0.410**	*0.047*	**0.451**	*0.051*	**0.403**	*0.081*	−1.7%
TDS [mg/L]	**464.000**	*3.000*	**546.000**	*44.000*	**579.000**	*53.000*	**544.000**	*94.000*	−0.4%
COD [mg/L]	**38.556**	*33.186*	**127.333**	*74.613*	**58.487**	*34.317*	**27.615**	*10.010*	−77.8%
Color [PCU]	**5.556**	*6.346*	**292.292**	*152.385*	**93.205**	*34.896*	**10.128**	*8.231*	−96.5%
Turbidity [NTU]	**0.871**	*0.611*	**79.508**	*66.965*	**10.797**	*6.417*	**1.682**	*0.514*	−97.9%
Alkalinity [mg $CaCO_3$/L]	**30.556**	*3.868*	**42.815**	*8.134*	**34.885**	*7.074*	**31.356**	*6.465*	−26.8%
BOD_5^{20} [mg/L]	**17.533**	*1.429*	**56.494**	*18.617*	**33.577**	*13.298*	**14.792**	*7.087*	−73.8%
Total coliforms [MPN/100 mL][a]	**Not tested**		**2.2E+05**		**3.9E+04**		**5.8E+03**		−97.4%
Oil and grease [mg/L][a]	**Not tested**		**0.30**		**0.03**		**0.02**		−93.1%

[a] Total coliforms and Oil and grease were only analyzed in three experimental runs.

wastewater batch volume. As the flow provided by the pump is higher than that of the ozonator, the excess is recirculated, reducing cavitation risks at the same time. Water coming from the ozonator is then sampled for the third and final time.

3. Results and discussion

3.1. Overall system performance

As previously mentioned in the method's description, most of the parameters were analyzed for thirteen experimental runs (except for total coliforms and oil and grease, tested only in the last three), with three samples taken at each corresponding point. Additionally, we tested nine samples from a groundwater well and wastewater downstream of the OWS to set a baseline before initiating the experiment. Table 3 summarizes this information and presents the treatment's efficiency by comparing wastewater from the OWS and reclaimed water.

As shown in Table 3, the average pH for all stages stood at medium-range values [6.6–7.8], with low coefficients of variation for each sampling point, allowing ozone to oxidize dissolved organic matter in neutral pH [49]. Alkalinity is a measure of water's capacity to resist sudden changes in pH, and it is determined primarily by the presence of hydroxides, carbonates, and bicarbonates [63]. Alkalinity levels in typical drinking water range between 20 and 200 mg/L. Low pH and alkalinity levels in water lead to corrosion in pipes, whereas high values cause precipitation, which is also detrimental [64]. In our experiment, the alkalinity behavior is consequent with pH, and both parameters' values in reclaimed water are similar to those from a groundwater source.

Dissolved oxygen is a water quality indicator because it directly influences aquatic ecosystems and wastewater treatment processes; it is also a parameter included in water reclamation standards [65]. The carwashing process reduces the concentration of dissolved oxygen to less than half of that measured in groundwater. Still, the system's coagulation-flocculation procedures help restore the values to adequate levels reported in carwash wastewater literature [66], an effect that might be an additional benefit of employing the airstone bubblers to perform the mixing.

A high COD to BOD ratio (COD/BOD >2.5) characterizes wastewater with a significant non-biodegradable organics fraction [67]. Based on Table 3, wastewater produced in the carwashing process falls within the COD/BOD medium range, with untreated domestic sewage characteristics with a low concentration of organics [63]. The results show that most organic matter removal occurs during the coagulation-flocculation process (69% for COD, 55% for BOD). The system was able to considerably reduce the BOD and COD concentrations in reclaimed water, resulting in levels comparable to those from the studies summarized in Table 1, and in terms of these two organic matter indicators, the average end product is of better quality than the groundwater resource.

One of the major concerns regarding water reuse for irrigation in developing countries is that raw or inadequately treated wastewater contains numerous pathogens and infectious agents, posing health risks for crop consumers and producers [63]. Coliform bacteria are considered reliable water-quality indicators based on the hypothesis that these organisms' presence in water could indicate recent fecal contamination [55]. For this experiment, we conducted coliform tests on samples from the final three experimental runs, with reclaimed water having an average total coliform count of around 5800 MPN/100 ml, which is above the proposed health risk limit of 1000 MPN/100 ml, indicating the need for additional disinfection [48,63]. We achieved similar removal rates and a lower final total coliform count than those reported in previous studies summarized in Table 1, and adding chlorination to the system could further reduce the count. Additionally [4], state that 200 MPN/100 ml of *E. coli* poses a low microbiological risk for car wash operators, a consideration to include in future studies.

The results in Table 3 indicate that oil and grease removal occurred in the filters and ozonator, which is in line with previous research findings [68,69]. As in the case of the coliform tests, oil and grease quantification was conducted only in the final

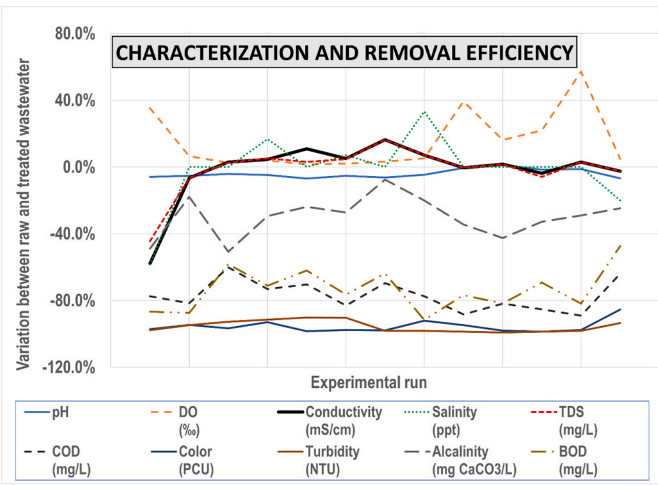

Fig. 2. Treatment efficiency as a function of time. Based on average values of the samples at each experimental run.

experimental runs, and future studies would require determining the backwash or replacement periodicity of the equipment based on more extensive data series.

Total dissolved solids (TDS) encompass inorganic salts and small quantities of organic matter dissolved in water. Regardless of the lack of specific health-based guidelines, TDS levels below 600 mg/L are considered suitable for drinking water and inadmissible when they reach values above 1000 mg/L [70]. Both TDS and EC are employed as water quality parameters (as salinity indicators), and can be measured directly by the equipment. According to the classification by Ref. [71]; the average EC values at all sampling points correspond to those of slightly saline waters, apt for crop irrigation. We set the EcoSense® EC300A to perform conductivity measurements with the temperature compensated to 25 °C. Besides an almost perfect correlation between the two series ($R^2 = 0.97$), the TDS/EC ratio remained consistent throughout all stages, with an average of 0.68 and a standard deviation equal to 0.08, comparable to natural water values [72]. indicates that the correlation between TDS and EC in wastewater is usually low due to the influence of many contaminants and the activity of specific dissolved ions, but the results suggest that this was not the case with our experiment.

Comparing wastewater from the OWS and reclaimed water from the ozonator, the treatment's efficiency did not exhibit clear increasing or decreasing trends in ten parameters monitored during the thirteen experimental runs. Fig. 2 presents the behavior of these series. Even if the sample size is relatively small, the absence of early clogging signs or a decline of the treatment capacity is a promising aspect of the system to be assessed in upcoming research to estimate the equipment's service life, a piece of essential information to evaluate the long-term or large-scale feasibility of the arrangement. Also, from a techno-economical perspective, and based on a 170-L average of water needed to wash a small car [30,57], the output from an employed ozonator would enable the treatment of the amount of wastewater equivalent to that required to wash 7 cars over a 10-h operation time. However, it is worth mentioning that the pump's flow rate enables upscaling of the overall system output by increasing the quantity or the size of the water treatment equipment.

Regarding the organoleptic characteristics of reclaimed water, the results indicate that the system can control the malodor sources, eliminate foaming, and generate an aesthetically favorable product, which is in line with previous research on wastewater treatment that included ozonation [49,61]. For illustration purposes, Fig. 3 displays one beaker with water from each sampling point, obtained from the twelfth experimental run, whose initial color and turbidity are similar to the mean values obtained from 48 samples collected downstream the OWS. The success of water recycling initiatives depends heavily on public acceptance, and the aesthetic characteristics of reclaimed water, including turbidity, color, and odor, are fundamental for this receptivity, mainly for recreation and household uses [73,74].

3.2. Comparing the results with the Colombian legislation

The Colombian Ministry of Environment and Sustainable Development promulgated Resolution 1207/2014 that regulates treated wastewater reuse [75]. Before this legislation, wastewater recycling was mainly limited to agricultural uses with little or no treatment at all [33]. While it is an advancement, the Resolution still requires further considerations and clarifications to encourage water reuse on a larger scale [56]. For instance, it does not specify which wastewater types are subject to reclamation, and only considers reclaimed water for its reuse on a limited set of industrial and irrigation activities, and carwashing is not among them. The results of this study might serve as a starting point for addressing this issue.

Besides Resolution 1207/2014 for treated wastewater reuse, Colombian legislation includes Resolution 2115/2007, which defines water's minimum characteristics required for human consumption [76], and Resolution 631/2015, which regulates parameter limits for wastewater disposal [77]. Even if this study did not evaluate the complete set of microbiological and chemical variables listed in these statutes, Table 4 presents comparable parameters that allow the reader to get a perspective on how reclaimed water from the system fares in terms of the Colombian legislation in force. An adequate wastewater treatment system reduces the pressure on the municipal infrastructure, receiving waters and decreases other environmental issues associated with raw wastewater disposal.

Table 3 shows that the on-site oil/water separator's implementation produces wastewater below industrial effluents' limits except for the BOD parameter. Aiming at assessing the potential reuse of reclaimed water, Table 4 indicates that the quality of treated wastewater collected at the ozonator is sufficient in terms of the analyzed variables for agricultural and most industrial uses considered

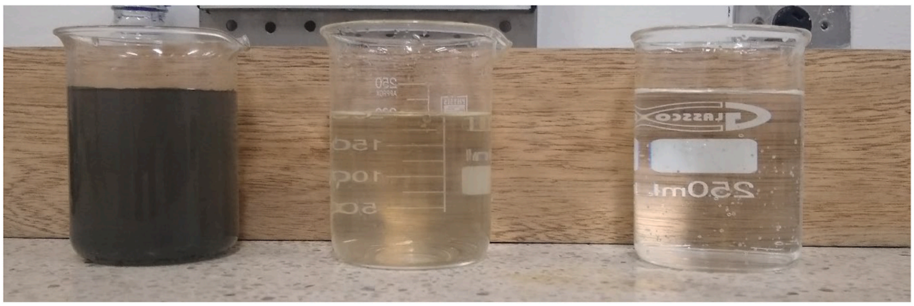

Fig. 3. Water samples from the twelfth experimental run. From left to right: i) from the oil/water separator (Turbidity: 75 NTU, Color: 365 PCU); ii) after the coagulation-flocculation process (Turbidity: 9 NTU, Color: 123 PCU); iii) after ozonation (Turbidity: 1.4 NTU, Color: 8 PCU). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Comparison between reclaimed water and legislation for the evaluated parameters.

PARAMETER[a]	Reclaimed water	Industrial discharge (Res 631/2015)	Reuse -Irrigation (Res 1207/2014)	Reuse - Industrial (Res 1207/2014)	Water for human consumption (Res 2115/2007)
pH [−]	7.22	[6–9]	[6–9]	[6–9]	[6.5–9]
Conductivity [mS/cm]	0.83		<1.5		1.00
COD [mg/L]	27.62	150.00			
Color [PCU]	10.13				15.00
Turbidity [NTU]	1.68				2.00
Alkalinity [mg $CaCO_3$/L]	31.36				200.00
BOD_5^{20} [mg/L]	14.79	50.00		<30	
Total Coliforms [MPN-CFU/100 ml]	5790		10,000[b]	1000[c]	0.00
Oil and Grease [mg/L]	0.02	10.00			

[a] Upper limits. The parameters in this list do not represent the whole set required by the referenced legislation.
[b] Upper limit for parks, sports fields, and garden irrigation. For agriculture different than for human consumption, a 100,000 MPN/100 ml is acceptable.
[c] This value is for most industrial applications. For fire sprinkler systems, the upper limit is 10 MPN/100 ml.

in the Colombian legislation, except for fire sprinkler systems [75]. Reclaimed water is also in compliance with the specifications related to human consumption, except for the coliforms count, which should be null in drinking water [70]. The allowed coliform count in the Colombian legislation in-force for the irrigation of parks, sports fields, and gardens in non-residential areas is above the acceptable concentration levels set out in other international standards, especially in the European Union and the United States. The recent review paper by Ref. [78] describes these strict regulations created to minimize the health risks stemming from irrigation with recycled water, such as gastrointestinal and dermal diseases.

4. Conclusions

This paper aimed to evaluate a bench-scale system's carwash wastewater reclamation potential based on coagulation-flocculation and household-grade activated carbon filter and water ozonation. The results from 13 experimental runs indicate that the reclamation system achieved a treatment efficiency of more than 70% for organic matter and 90% in color and turbidity, with similar removal rates in the last three experimental runs that also tested the elimination of coliforms and oil and grease. For most water quality variables under analysis, the reclaimed water exhibited characteristics comparable to those of a groundwater source, suggesting promising signs for similar carwash wastewater treatment systems. Nevertheless, a more extended observation period in future research would help determine the equipment's effective service life, a piece of essential information for its long-term techno-economic viability and implementation.

The reclaimed water meets most agricultural, industrial, and even drinkable water quality standards provided in the Colombian legislation in force for water quality variables specified in this study. The total coliforms count is above the acceptable limit for fire sprinkler systems and water for human consumption, indicating that the system might benefit from chlorination or another process improving the removal rate of this pollutant. Additional research directions might include the potential reuse of the sludge produced in the reclamation process. We hope this research results may assist future carwash wastewater reclamation regulation in Colombia and the Latin American region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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