World Environment 2021, 11(2): 83-98
DOI: 10.5923/j.env.20211102.02

Contemporary Carwash Wastewater Recycling Technologies: A Systematic Literature Review

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Abstract Faced with dwindling freshwater resources globally, many industries, including the carwash industry, have turned to wastewater recycling technologies. But the performance of these technologies, their environmental impacts, and economic viability have not been extensively examined. This systematic review examined the treatment efficiencies of modern carwash wastewater recycling technologies, their cost implications, and their by-products. The study drew on an extensive literature search spanning the last decade and found 34 research articles suitable. The results showed combined treatment methods as the most typical approach adopted for treating carwash wastewater. Combined technologies incorporating membrane filtration process almost completely remove COD (99%) and turbidity (99%), but flux reduction and membrane fouling present significant problems. Other technologies employing chemical or electrochemical coagulation produce sludge containing hydroxide and oxyhydroxide ions. But this sludge is mainly landfilled. The highest capital and annual operational costs for the technologies assessed are about US$10,000 and US$3000, respectively. The payback period ranged between 5 and 140 months and saves up to 5000m^3 of freshwater annually, translating into savings of about US$20,000 yearly. This study generally observed an extensive focus on the treatment efficiencies of CWW recycling technologies to the neglect of their economic viability and environmental impact. Areas for further studies are discussed in the paper.

Keywords Carwash wastewater, Treatment, Economic analysis, Sludge, Recycling

1. Introduction

Car wash wastewater recycling (CWWR) technologies have been used for at least three decades and are rapidly growing in sophistication [1]. These technologies treat previously used wash water to remove impurities and reuse it in the wash process again. CWWR is practised as a way of conserving water in many countries. In a world faced with an increasing decline in freshwater availability, sustainable water management is considered imperative. Therefore, various countries have enacted laws that demand a wastewater recycling system and restrict water usage at car washing stations [2]. In response, car wash operators found in such regions have adopted environmentally friendly and modern technologies to save energy and conserve water [3]. However, while these countries apply stringent measures to control water wastage by car washes, others, mainly in developing and less developed countries, do not have such regulations [4]–[6]. Consequently, vast amounts of fresh water are wasted daily from car washing activities.

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Received: Nov. 25, 2021; Accepted: Dec. 20, 2021; Published: Dec. 29, 2021
Published online at http://journal.sapub.org/env

Besides wasting water, car washes also contribute significantly to water pollution. Effluents from these activities are known to contain high levels of COD, TSS, Sulphates and other pollutants, which can be very harmful [4], [7]. Therefore, many treatment technologies including, electrochemical, membrane processes, and chemical coagulation [8]–[11], have been developed to avoid discharging untreated carwash wastewater into the environment. These technologies may seem feasible in some parts of the world but may not be possible in others due to economic differences. Meanwhile, available studies [12], [13] only focus on the type of technologies and their performance without considering the financial aspects (capital and operation expenditure, payback periods and revenues) and sludge production and disposal methods. Particularly in the developing world, where regulations do not exist to compel carwash operators to recycle wastewater, the only motivation to install a CWWR technology is the operational cost reduction benefit. The economic aspects of contemporary CWWR technologies thus need to be studied to inform future studies that would seek to reduce the capital and operating costs of the technologies.

Moreover, these CWWR technologies may generate by-products requiring treatment before disposal and therefore becomes imperative to assess how the current technologies are handling these by-products. Therefore, this systematic review examines the diverse CWWR technologies available, their treatment efficiencies, financial implications, and sludge production and disposal methods. This is to extend the current boundary of existing knowledge and provide the basis for future studies on CWWR.

2. Materials and Methods

2.1. Literature Search and Selection Criteria

The search was carried out using keywords and phrases that are relevant to the study being conducted. Databases where searches were conducted are PUBMED, ScienceDirect, Taylor & Francis and Google Scholar. The search was limited to only articles published in English and those published in the past decade: on or after 2010 up to 2020. Articles selected were those that were available electronically. The keywords and phrases were meshed, and where supported, wildcards were also included in the search strings to ensure all relevant documents were captured. The mesh terms used were as follows; [(‘carwash’ OR ‘carwash’, OR car wash’ OR ‘vehicle wash’) AND (Treatment OR Recycle OR reclaim OR reuse) AND (wastewater OR effluent)].

2.2. Screening

The search from the four databases using the provided keywords and mesh terms returned 1,363 articles (Figure 1). These were then screened based on their relevance to the scope of the review. Titles and abstracts were used initially to obtain articles relevant to this work. Afterwards, a manual inspection of the relevant articles was done to further screen them based on specific inclusion and exclusion criteria. Articles included in this manual screening were those that qualified the inclusion criteria. The inclusion criteria were that articles should have information on carwash wastewater, the characteristics of the wastewater, a treatment method for the carwash wastewater, results for the treatment method used, and/or financial and sludge disposal aspects. Articles to be selected would have to meet these criteria. Other articles were also obtained from the bibliographies of selected articles during the manual inspection. After careful manual inspection, the number of articles was thinned down to 46. Since the searches were done in 4 different databases, duplicates were expected to manifest. Out of the 46 articles, 12 were duplicates. So eventually, 34 relevant articles were left for use in this study (Figure 1). The list of all articles used in this study is provided in the supplementary sheet.

3. Results and Discussion

The results indicate that combined treatment technologies were the predominant method adopted for treating carwash wastewater (Figure 2). They involve two or more biological, physical, chemical, and electrochemical processes in treating carwash wastewater (CWW). The least applied were other advanced and complex methods, biological processes and treatment by coagulation and sedimentation only [10], [14]–[17]. Membrane processes were the second most common method. They were mainly applied as secondary treatment, preceded by coagulation and/or sedimentation, or as a tertiary treatment after sand filtration. Membrane processes show high removal efficiency for turbidity and COD, but this depends on the membrane pore size being used. However, due to the various pollutants found in CWW, an integrated technology that combines different processes (which may or may not include membrane processes) is perceived to be the better option [2], [18], [19]. Nonetheless, reusable treatment standards can be achieved either by membrane processes only or an integrated system.

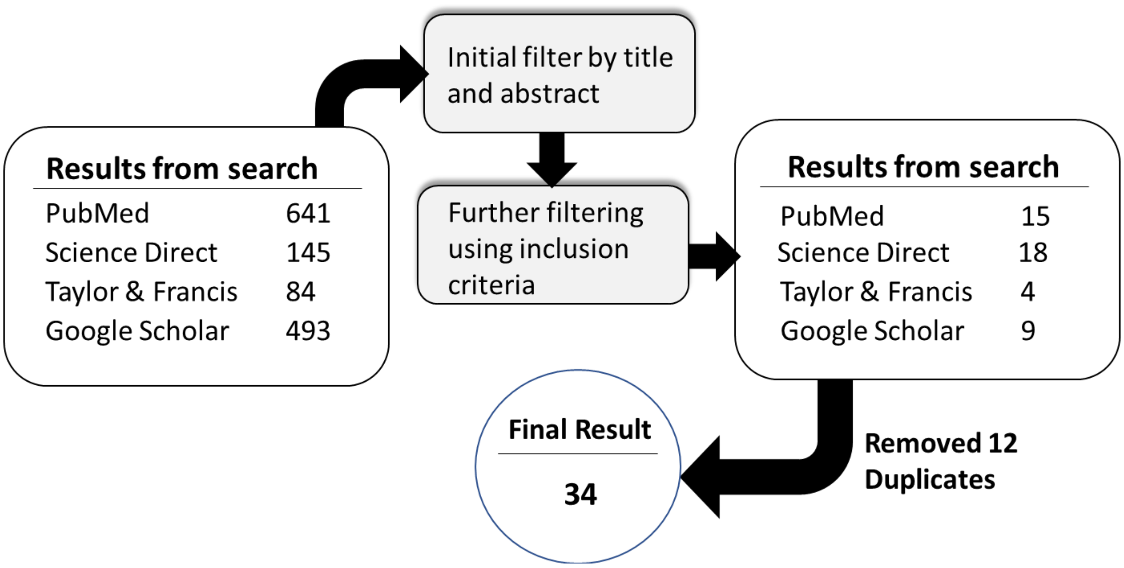

Figure 1. The search and screening process flow chart

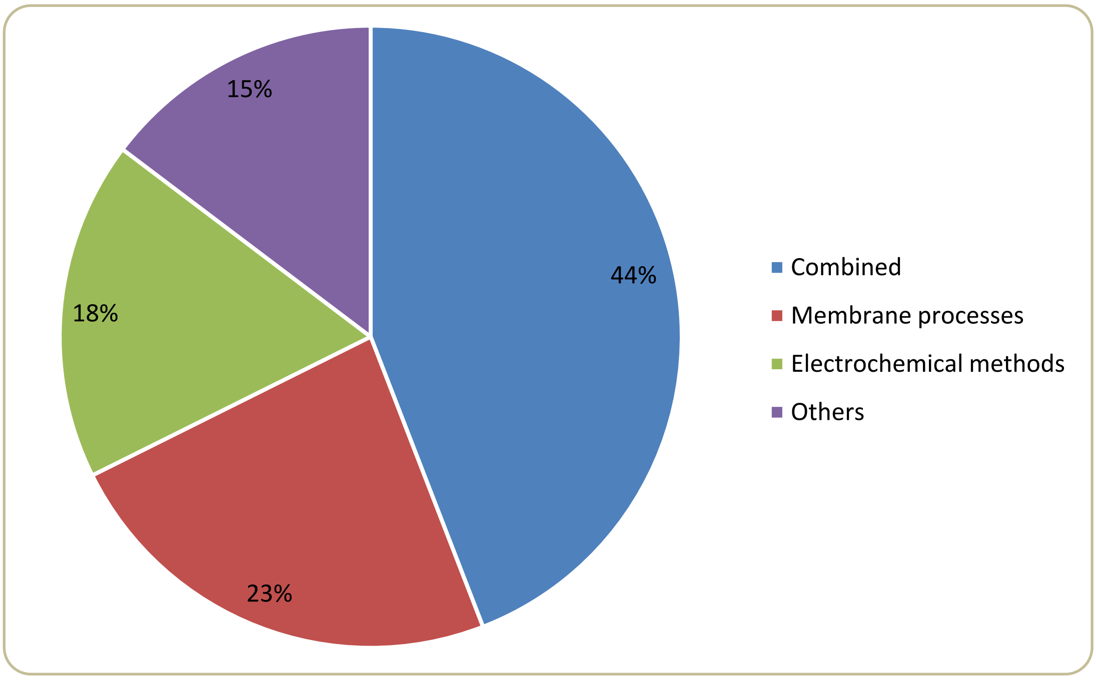

Figure 2. The proportion of different technologies applied in treating CWW

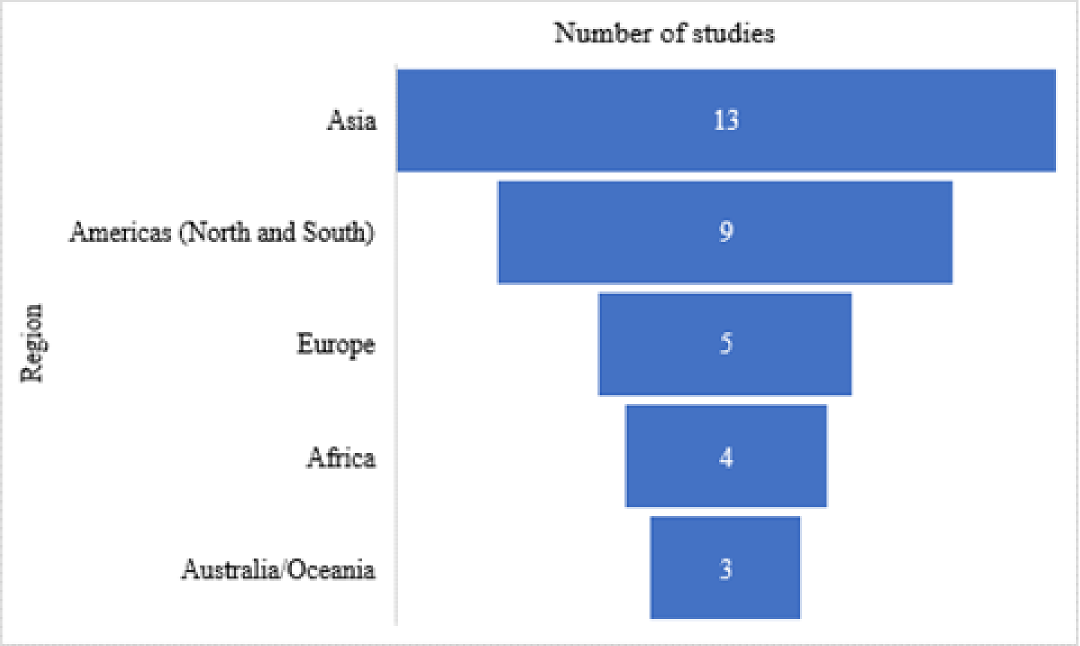

Figure 3. Distribution of articles published per region

The review also revealed how most of these technologies are distributed worldwide (Figure 3). From the 34 selected articles, 4 of these studies were conducted in Africa [17], [20]–[22]. More than half (62%) were from Asia and the Americas.

3.1. Performance of CWWR Technologies

The type of technology adopted for treating CWW depends on the nature of pollutants and the end use of the treated water. Carwash wastewater that is treated for discharge is mainly achieved through pre-treatment methods, while highly polluted waters either go through both pre-treatment and biological processes, membrane filtration, oxidation and/or adsorption processes [14], [16], [23]. Pollutant concentrations reported by numerous studies differ for different study locations, so other methods and technologies have been applied in different regions for treating CWW. Subsequently, the various technologies reviewed in this study and their pollutant removal efficiencies are presented.

3.1.1. Electrochemical Processes

Removing pollutants from wastewater using electrochemical processes is a relatively modern technology that uses the concepts of electricity and chemistry. It has proven to be proficient in removing turbidity and surfactants in CWW [24]–[26]. According to this review, it is the third most used technology in treating CWW. Electrochemical methods include electro-coagulation and electro-oxidation. While the former is popular in treating CWW, the latter is not very prevalent in the carwash industry. Electrochemical processes use electrodes to aid in the treatment of wastewater. For example, in an electro-coagulation process, an electrode is oxidised continuously while an electric current is being applied. This leads to the release of ions that disturb the stability of the suspension and facilitate particle clustering and settling [26].

The main parameters that affect the performance and efficiency of an electrochemical process are electrode material, voltage/current density, pH and contact time [21], [24]–[27]. The electrode material commonly adopted are Aluminium (Al) and Iron (Fe). These are used separately or combined in the treatment process. The initial pH affects the stability of generated hydroxide species in the electro-coagulation process [26]. Therefore, the removal efficiencies increase as pH is increased. A study by [25] reported 99% turbidity and 88% removal of COD for Al electrode and 94% turbidity and 73% COD removal for Fe electrode at a pH of 7, a voltage of 30V and contact time of 90 minutes (Table 1). They observed that increasing the voltage caused a significant increase in removal efficiency. However, the amount of voltage supplied is related to the energy consumption, which is related to the cost of operation. Therefore, a reasonable compromise must be made in choosing the proper voltage that does not increase the operating cost too much [26]. While others reported electricity supplied to the electrochemical process in volts [25], [27], others also reported it in current density [21], [24], [26]. The current density (CD) is defined by [24] as the current per area of the electrode.

Increasing the voltage or current density releases a greater number of ions that precipitate with pollutants in the wastewater. This creates tiny bubbles that improve floc generation for pollutant removal [24]. [26] reported that increasing the current density from 53 A/m^2 to 210 A/m^2 increased the removal efficiency of COD and turbidity (Table 1). At a pH of 7, contact time of 60 minutes and CD of 210 A/m^2, 95% and 84% of turbidity and COD were removed respectively with an Aluminium electrode and 94% and 80% turbidity and COD removal with an Iron electrode. Another parameter of interest that also affects the performance of the electrochemical processes is contact time. The contact time is also inversely related to Voltage or CD. If the current density or the voltage decreases, more time is needed to achieve higher efficiencies and vice versa [26], [27]. According to the study, the optimum contact times ranged from 30 minutes to 120 minutes. [26] again reported results on electro-oxidation after performing the electro-coagulation. The results revealed that a higher contact time of 120 minutes could remove 100% oil-grease, 99% colour, 98% turbidity, 96% COD, 93% Biological Oxygen Demand (BOD) and 92% Methylene Blue Active Substances Assay (MBAS) and 90% chlorides. [21] also looked at another parameter; temperature. Per their study, the temperature can potentially impact the performance of the electrochemical treatment process significantly. However, their observation of a temperature change from 30 to 45℃ were insignificant.

Table 1. Electrochemical Processes

Reference	Processes	Treatment results	Country of study
[25]	Electrocoagulation with aluminium(Al) electrodes	Removed 75% and 99.59% of turbidity at 10V and 30V respectively with optimum pH of 7. Also removed 67 and 94% of COD at 10V and 30V respectively with an optimum pH of 3	Iran
[26]	Electrocoagulation (Al and Fe electrodes) and Electrooxidation	The combined process (EC; Al electrode pH=7, current density=150A/m^2 for 60min, EO; BDD electrode at 210A/m^2 for 120min) reduced oil by 100%, colour 99.3%, turbidity 98.4%, COD 96%, BOD 93%, and methylene blue active substances 92%.	Mexico
[21]	Electro-coagulation with Aluminium and Iron electrodes	The aluminium electrode was more effective in removing COD and turbidity. Maximum removal occurred at an optimum pH of 8.	Egypt
[27]	Settling, Chemical coagulation with Poly Aluminium Chloride (PACl) and Electro-coagulation with Aluminium electrodes	The system had COD, BOD, TSS and MBAS removal rates of 96.87%, 94%, 98.43% and 98.62%, respectively. Efficiency increased with an increase in PACL dosage and applied voltage. The optimum PACL dosage was 100mg/L at an applied voltage of 40.	Iran

3.1.2. Membrane Treatment Processes

Membrane technologies involve using a porous material for the transport of substances between two factions. It can be used for the separation of both gaseous and liquid streams. This process has been widely used to treat different types of wastewater [28]. It has proven very efficient in removing pollutants like Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS) and turbidity. According to this review, membrane treatment methods constitute the second most common technology adopted in treating CWW.

For the effective and reliable performance of membrane technology in treating CWW, the membrane material should be highly permeable, have high flux and have low retention [29]. However, the problem with using membranes to treat CWW is the reduction in flux over time and membrane fouling [11], [19], [30], [31]. The flux can decrease drastically to about 60% of the initial flux over a short time [19]. The loss in flux is dependent on membrane pore size, influent quality and type of membrane material [19], [28], [31]. Nanofiltration membranes generally perform better than Micro and Ultrafiltration membranes in terms of fouling and flux decline. Membranes with hydrophilic and negatively charged surfaces also prevent significant flux decline and reduce fouling [30], [31]. The hydrophilicity of the membrane can be achieved by modifying it with bentonite and sulphonate polyether ether ketone (SPEEK) [32]. Other studies ([28], [33]) also reported that pre-treating the membrane influent can significantly increase the flux to about three times higher than when the influent is not pre-treated.

Transmembrane Pressure (TMP) also significantly affects the membrane's flux. An increase in the pressure causes an increase in flux. However, too much pressure increase can reduce permeate quality or even lead to severe fouling, which might deteriorate the membrane's lifetime [11], [19]. Higher pressures also translate to higher energy consumption, leading to a high cost of operation [19].

Regarding treatment efficiencies (Table 2), membrane filters (micro, ultra and nanofillers) can produce permeate with high-quality standards. Turbidity, COD, TDS concentrations in permeate are well within acceptable ranges for reuse or discharge. COD removal efficiencies recorded varied from 60% to as high as 99.2% [11], [19], [30], [32], [34]. Complete COD removals are achieved when a biological process (Membrane Bioreactor) precedes the membrane process (Table 2). This is true when microorganisms in the bioreactor are stable [11], [34]. Other studies reported 99% [19], 88.6% [30] and 98.8% [32] removal of turbidity from CWW using membrane processes (Table 2). Removal efficiencies of pollutants like Total Organic Content (TOC) and Total Nitrates were also reported to be 97.3% and 60%, respectively [11], [34]. Reducing electrical conductivity was the most difficult to achieve by membrane processes [19], [30]. However, incorporating an ion exchange process or a reverse osmosis process has been shown to overcome this, thereby increasing the cost of operation.

Membrane treatment methods are beneficial due to their low space requirements [33] and short treatment time [32]. However, fouling and flux decline seem to be some of the challenges with its use. Many approaches to reducing flux and fouling are available, but they do not completely eradicate these problems.

Table 2. Membrane Processes

Reference	Processes	Treatment results	Country of study
[28]	20-micron filter pre-treatment followed by micro and nanofiltration	The 20-micron filter achieved less than 20% COD, conductivity, and colour removal. Further treating with Microfilter improved efficiency but additional nanofiltration achieved a total of 98% COD and colour removal	India
[11]	An enhanced membrane bioreactor (a membrane process with biological pre-treatment)	More than 99% removal of COD and 63% removal of Total Nitrogen. Turbidity was reduced to between 0.8 and 0.4 NTU. Disinfected effluent had zero microbes present per 100ml	Australia
[19]	3 micro and 1 ultrafiltration membranes	Removed up to 99% of turbidity (dependent on membrane pore size) and up to 85% reduction in COD	Brazil
[31]	4 ultrafiltration membranes, settling and 100-micron filter pre-treatment	Removed 98% COD and 47% reduction in conductivity.	Turkey
[32]	Ultrafiltration with modified membranes (Hydrophilic sulfonate poly ether ether ketone and bentonite used as additives for membranes) and commercial membranes	The modified membranes performed better than commercial membranes with a more stable flux. Modified membranes removed 60% and 82% of COD and Turbidity whiles commercial membranes removed 46% and 77% COD and turbidity	India
[30]	Nano and Ultrafiltration (2 nano filters and 1 ultrafilter)	Turbidity reduction of up to 98%, COD up to 91%, TDS up to 61% and conductivity up to 63% was achieved	Malaysia

Table 3. Combined Processes

Reference	Processes	Treatment results	Country of study
[33]	Sedimentation and flotation pre-treatment. Ultrafiltration and reverse osmosis	100% turbidity, 82% TDS, 91% TSS, 81% COD and 90% oil-grease removal	India
[34]	Coagulation pre-treatment. Membrane Bioreactor	the MBR showed 100% removal of suspended solids, 97.3% removal of TOC, 99.2% of COD and 41% of Ammonia	Australia
[24]	Electro-coagulation with Iron (Fe) electrode and Nano Filtration (2 Nano filters)	System removed 88% COD, 90% oil-grease, 92% chlorides, 80% conductivity and 90% hardness	Turkey
[23]	Coagulation and flocculation (Tan floc), sedimentation and adsorption w ith mineral activated carbon	Overall, the processes were able to remove 97.3% colour, 98.8% turbidity 92.6% COD and 97.2% surfactants	Brazil
[37]	Coagulation, Sedimentation and Sand Filtration	80% TSS, 32% TDS and 98.5% turbidity reductions	Pakistan
[22]	Coagulation(Comparison between Alum synthesised from bauxite waste and Industrial Alum), sedimentation/flotation and sand filtration	99%, 34%, and 75% turbidity, anionic surfactants, and COD reductions respectively for synthesised alum. Industrial grade alum removed 100% turbidity, 37% surfactants and 74% COD	Ghana
[41]	Coagulation-flocculation (Ferrous sulphate), sedimentation and sand filtration	Presented only design parameters, fixed, and running cost of the system but no information on the treatment results	Pakistan
[18]	Coagulation (Ferric chloride over Alum), sedimentation, sand filtration, Ultrafiltration with ceramic membrane and reverse osmosis	Overall, 99.9% turbidity reduction, 100% removal of suspended solids and 96% COD removal	Australia
[38]	Biological treatment, sand filtration and Ultrafiltration (as a check to compare treatment efficiency)	Initial biological and sand filtration treatment yielded 79% turbidity, 79% colour and 53% BOD reduction. Additional Ultrafiltration removal efficiency to 94% for turbidity, 86% for colour and 86% for COD	Brazil
[39]	Coagulation (Tan floc SL), Flocculation-Flotation, sand filtration and ozonation for disinfection	Treatment provided clarified water of 10 NTU and surfactants concentration of 1.3mg/L MBAS with no odour. Disinfection resulted in less than 1.8CFU 100m/L	Brazil
[3]	Sedimentation and sand Filtration	No information on treated water parameters. Provided information on the capital cost of installing the system	India
[40], [42]	Coagulation (PAC or Tan floc), sand filtration and chlorination	The full-scale operation was able to reclaim 70% of clear odourless water with average turbidity of 9NTU. Acceptable E.coli concentration of 200CFU per 100mL was achieved with chlorination (15mgCl2/L)	Brazil
[20]	Coagulation and flocculation (ferric chloride), sand filtration, oxidation and activated carbon adsorption	COD and Turbidity removal of 80% and 100%, respectively	Egypt
[2]	Biological treatment (hydrophilic bio-carriers) and membrane filtration (2-micron pore size)	The full-scale system was efficient in removing COD, TOC, and SS. Final effluent quality like tap water	Taiwan
[43]	Coagulation (Tan floc SL), flocculation-column-flotation, sand filtration	The full-scale system showed 70% of odourless and clear water was reclaimed in the carwash requiring less than 40L of freshwater use	Brazil

3.1.3. Combined Processes

Looking at the different pollutant compositions of CWW, a single treatment step will not be enough to remove all these pollutants altogether. Therefore, it is essential to complement it with other technologies that can effectively handle these diverse pollutants. This is where combined processes come into play. The idea is to integrate different treatment methods in the most cost-effective way that produces greater removal efficiencies for several types of pollutants found in CWW. Also, full-scale application of treatment systems mainly combines at least two or more treatment processes as it is more feasible, rational and economically viable than a single treatment step [35]. Literature from this review validates this statement. Table 3 shows the treatment efficiencies of combined processes reviewed in this study. All the full-scale CWW treatment technologies examined in this study were combined processes. Although the different combinations can yield better treatment efficiencies, the removal efficiency for a particular pollutant depends on the treatment methods combined for the treatment chain.

A combination of coagulation, flocculation, sedimentation and adsorption by [23] resulted in a superb wastewater clarification with fairly efficient removal of COD and surfactants initially. After they improved the treatment process by adjusting certain features, COD and surfactant removal increased to 81.1% and 92.1%, respectively. Both [36] and [37] applied the same combined process of coagulation, sedimentation, and sand filtration to treat CWW. Although [36] did not report on the removal efficiencies, [37] reported a reduction of turbidity from 253 to 3.7NTU, hardness from 321.60 to 120mg/L and oil-grease from 27 to 14mg/L. [22] also employed coagulation, flocculation-flotation and sand filtration processes in their study and produced high-quality treated water with COD, anionic surfactants and turbidity removals of 99%, 92% and 100%, respectively. Their system had little to no effect on TDS and EC.

Most integrated systems can adequately deal with Suspended Solids, COD, oil- grease and surfactants. The major limitation lies in the TDS and EC concentration of the wastewater. Depending on the treatment methods used in the combined process, there could be a build-up of certain compounds that the system could not remove [38]. TDS is one of those parameters. Reducing TDS and EC requires adopting expensive processes like reverse osmosis in the treatment process [18], [19]. TDS is sometimes used as the limiting factor to determine the percentage of the wastewater recycled, leading to no further increase in TDS concentrations when the treatment system shows little to no effect on it [38]–[40]. In the study conducted by [40], where Flocculation column flotation, sand filtration and chlorination were applied in treating CWW, TDS concentration was seen to increase after treatment with chlorination. To prevent corrosion and scaling risk of cars being washed by the accumulation of TDS in the reclamation process, the TDS concentration limit was set at 1000mg/L (potable standard in Brazil). This resulted in 70% CWW reclamation, which is supplemented by 30% of freshwater. [38] also combined a biological treatment with granular filtration and membrane filtration processes to treat CWW. Their system also had an insignificant effect on TDS reduction. To prevent accumulation from reclamation, a mass balance equation with TDS as a limiting factor was used to determine the percentage of the wastewater to be recycled. A 200mg/L TDS limit resulted in a 40% reuse of treated water. Also, they reported that up to 70% of treated water could be reused when applied only for pre-rinse. This will eventually increase the TDS to a maximum of 850mg/L, which is an acceptable concentration.

[18], in their study, which aimed to produce high-quality wastewater for reuse in car washing stations, combined ceramic ultrafiltration, sand filtration, coagulation / flocculation sedimentation and reverse osmosis to treat wastewater for a carwash station. The system had an overall removal efficiency of 99.94% turbidity, 96% COD, 98% EC, 100% TSS and 100% phosphorus. The treated water quality produced was very high, which met the required standard A for recycled water in Australia. [2] also applied an integrated biological and membrane process - Bio-MF, which yielded water quality like tap water. A hybrid process involving several processes; coagulation/flocculation sand filtration, oxidation and final sand and carbon filtration by [20] produced an overall COD and turbidity removal to 88% and 100%, respectively.

3.1.4. Advanced Oxidation (Photo/Electro – Fenton Process)

Advanced oxidation processes utilise hydroxyl radicals to remove organic pollutants from wastewater. They have been widely used to treat different types of wastewater [44]. One of such processes is the Fenton process – a process that generates a hydroxyl radical (OH) from the reaction between aqueous ferrous ions and hydrogen peroxide (H_2O_2). A modified version of Fenton process (photo/electro-Fenton) has been applied in treating CWW [8], [17]. An advantage of this modified process is its ability to regenerate Fe^{2+} ions needed as a catalyst to facilitate the oxidation process [45]. The process, just like many other treatment processes, depends on certain factors to be effective in its pollutant removal capabilities. Nevertheless, the process has proven effective in completely removing surfactants and COD from carwash wastewater [8] (Table 4).

However, the efficiency of the electro-Fenton process is affected by pH, applied current, electrode material, the concentration of iron ions and its nature (Fe^{2+}, Fe^{3+} or solid Fe III). Moreover, the photo-Fenton process is also affected by pH, H_2O_2 concentration and Fe^{2+} concentration. The study by [8] compared three types of advanced oxidation processes: electro-oxidation, electro-oxidation with H_2O_2 generation and electro-Fenton's process, to remove surfactants and COD from CWW. All three processes were performed with acidified wastewater (pH=3). Their electrochemical advanced oxidation treatment employed a Boron-doped diamond thin film (BDD) anode and a carbon felt cathode. The removal efficiency was more remarkable for the Electro-Fenton process than the other two methods. It completely removed COD at a contact time of 6 hours and current of 500mA, and 96% surfactants at a contact time of 4 hours and current of 500mA. The removal efficiency of the process was improved when the current was increased from 250 to 1500mA. However, this also resulted in significant energy consumption. Complete removal of surfactant was achieved at 1500mA of current at a lesser contact time of 1hour.

Another study by [17], which involved using the photo-Fenton process as an advanced oxidation treatment method for treating CWW, saw almost complete (97%) COD removal from the CWW (Table 4). They used a UV source for the photo-Fenton process coupled with Fenton's reagents (H_2O_2 and Fe^{2+}). Concentrations of H_2O_2 and Fe^{2+} significantly influenced removal efficiency. Increasing these parameters saw a significant increase in COD removal. However, raising them beyond a particular concentration saw a decline in removal efficiencies. pH also played an essential role in the processes. A pH of 3 was considered the optimum for higher removal efficiencies.

3.1.5. Biological Treatment

Biological wastewater treatment involves using living organisms, especially microbes, to remove pollutants (primarily organic) from wastewater. It is commonly used to complement and enhance traditional treatment methods [46]. It is considered simple and less costly than other chemical and physical processes. There have been a handful of biological treatments applied in treating CWW. Since the biological treatment alone cannot eliminate the different pollutants in CWW, they are usually combined with other treatment methods to effectively remove these diverse pollutants in the wastewater. [2], [11] combined biological treatment with other processes to treat CWW. The biological treatment was used alongside a membrane filtration process, and eventually, they reported a significant decrease in the organic content of the CWW. [38] also combined biological treatment (Rotating Biological Contactors) with granular filtration to treat wastewater from a heavy-duty car wash station. Their system had overall removal of 79% turbidity and 86% BOD (Table 4). Chlorine was applied at the end of the process to deal with biological contaminants present in the wastewater. Grab samples from their system were additionally treated with an ultrafiltration membrane which further improved the treated water's quality.

Table 4. Other Treatment Methods (Biological, Advanced oxidation and Complex processes)

Reference	Processes	Treatment results	Country of study
[10]	Coagulation and flocculation using Polyaluminum chloride, Iron 3 chloride, Iron (II) sulphate, Aluminium chloride, non-ionic and anionic polyelectrolytes	Removed 98% turbidity, 59% COD and 85% extractable oil content from car wash wastewater	Hungary
[8]	Advanced oxidation processes (electro-oxidation, electro-Fenton process, electro-oxidation with hydrogen peroxide generation using boron-doped diamond thin film anode and carbon felt cathode)	Complete removal of anionic surfactants and excellent removal of organic matter	Brazil
[16]	Cascaded constructed wetland using 3 plant species: ribbon grass, water mint and divided sedge as Phyto-remediators for removing surfactants	Optimum treatment (Hydraulic retention time of 6days) yielded outlet surfactant concentrations of 0.07 - 10.20 for ribbon grass, 0.10-9.10 for water mint and 0.11-9.50 for divided sedge for inlet surfactant concentrations ranging from 10mg/L to 100mg/L.	Italy
[17]	Advanced Oxidation (Photo-Fenton process that utilises UV source coupled with photo-Fenton's reagent [Fe2/H202])	Achieved COD reduction of up to 97% at an optimum pH of 3.5 and molar ratio of Fe_2:H_2O_2 at 12:1	Egypt
[15]	Coagulation (comparing commercial and natural coagulants)	At the same dosage, *Moringa oleifera* removed 90% turbidity, 60% COD and 75% phosphorus. *Strychnos potatorum* also removed 96% turbidity, 55% COD and 65% phosphorus. Alum and Iron Sulphate removed 87% and 77% turbidity, 74% and 71% COD, 81% and 65% phosphorus, respectively.	Malaysia

From the articles reviewed for this study, one study reported a stand-alone biological treatment for CWW [16]. The authors designed a Phyto-remediation treatment system for the removal of anionic surfactants in CWW. Their setup involved a wall cascade constructed wetland (WCCW) with a surface area of $7.5m^2$ vegetated with three plant species namely, *Typhoides arundenacea* (L.) Moench (ribbon grass), *Menta Aquatica* (water mint) and *Carex divisa Hudson* (divided sedge). The cascade had three levels, with each level containing three constructed wetlands in a container, each vegetated with the three plant species. The wastewater feed was self-made synthetic wastewater to mimic real CWW containing surfactants. Surfactant concentrations varied from 10mg/L to 100mg/L. Their setup was run for 105 days and monitored over 15 cycles. For every cycle, plant growth, inlet and outlet wastewater samples and consumption by the plants were monitored. Their system removed as high as 99.5% of anionic surfactants from the carwash wastewater. The removal efficiencies depended on the Hydraulic Retention Time (HRT) and the inlet surfactant concentration. *Tyhoides arundenacea* and *Carex divisa Hudson* plants had their removal efficiencies increasing with increasing HRT while *Menta aquatica* had the opposite effect. *Menta aquatica* also consumed a greater portion of the inlet wastewater volume, producing outlet volumes as low as 35% of the inlet volume. This is not a good recovery rate suitable for reuse at commercial carwash stations. The choice of plant selection should be based both on reduction efficiency and water recovery of the selected plant species that yields the maximum effluent volume.

Their study demonstrates the effectiveness of biological treatment in removing organic pollutants. It follows that the adsorption of substrate and biodegradation by bacteria plays a significant role in eliminating anionic surfactants from wastewater. The operation of their system was simple, with less energy supply and construction cost. However, it is not suited for removing the different pollutants present in CWW.

3.1.6. Simple and 'Complex' Coagulation Processes

Wastewater from various sources commonly contains organic and inorganic particles, which make it turbid and give it colour. CWW also contains these particles. Coagulation, a process that involves the destabilisation of particles found in wastewater to promote their agglomeration into larger particles (flocs) for easy settling and removal, has been reported to be efficient in reducing organic and inorganic particles concentration and improving turbidity of the wastewater [46]. It is mostly performed in traditional water treatment processes as a pre-treatment step to reduce pollutant load before other chemical, physical or biological treatment methods are applied to the wastewater [47]. Similarly, it has been applied in treating CWW and reported to be efficient in removing turbidity, colour and COD from CWW [15], [22], [42].

In all the treatment technologies reviewed in this study, more than 70% employs coagulation in their processes. The most commonly used chemicals for coagulation are Aluminium and Iron salts. However, other natural organic substances and electrochemical methods have been equally adopted to achieve the same outcomes. Table 5 shows a list of different coagulants applied in CWW treatment technologies. As mentioned earlier, coagulation processes are not performed in isolation. However, [15] conducted a study to compare the efficiency of coagulants alone in treating CWW. They compared natural coagulants; *Moringa oleifera* and *Strychnos potatorum*, with chemical coagulants; Alum and $FeSO_4$ [Iron (II) Sulphate]. While Alum and $FeSO_4$ performed better in removing COD from the CWW, with removal efficiencies of 80% and 77%, respectively, *S. potatorum* performed better in removing turbidity (95% reduction) at a lower dosage concentration of 50mg/L. However, when they compared the efficacy of both coagulants in removing phosphorus, the chemical coagulants performed better (85% removal efficiency).

Table 5. Types of coagulants used in car wash wastewater treatment technologies

Type of Coagulant used	References
Alum (industrial/ commercial)	[14], [15], [18], [22], [34], [37]
Alum synthesised from bauxite waste	[22]
Tanfloc	[23], [39], [42]
Moringa Oleifera	[15]
Strychnos potatorum	[15]
Iron III Chloride	[10], [18], [20]
Iron II Sulphate	[10], [15], [41]
Polyaluminum Chloride	[10], [27], [34], [42], [43]

Coagulation processes can also be enhanced by adding certain chemicals to conventional coagulants. The addition of these additives is what [10] describes as '*complex coagulation'*. They applied their complex process, which involved the addition of non-ionic and anionic polyelectrolytes, Na bentonite and hexadecyltrimethylammonium bromide (HTABr), to three conventional coagulants, Polyaluminum chloride, Iron (II) chloride and Iron (III) sulphate. The optimum concentration of Na bentonite, polyelectrolytes and HTABr that yielded the best results were 100mg/L, 0.5mg/L and 500mg/L, respectively. Out of the three coagulants, poly aluminium electrolyte had the highest removal efficiency, almost completely removing (98%) turbidity from the CWW with only Na Bentonite. Also, at the same concentration of 20mg/L with the addition of optimum dosages of electrolytes, HTABr and Na bentonite, $57\pm3\%$ COD and $83\pm3\%$ oils reductions were observed. The addition of HTABr did not significantly affect the removal efficiencies, but it reduced the amount of sludge generated from the process.

The efficiency of chemical coagulation processes is mainly dependent on coagulant dosage and wastewater pollutant loads [15]. Highly turbid wastewater will require higher concentrations of coagulant. Higher coagulant dosages may also alter the wastewater's pH and cause a rise in TDS and COD depending on the type of coagulant being used [15]. Natural coagulants and tanning based coagulants do not significantly alter the pH of wastewater at high dosages [15], [42].

3.2. Sludge Characterisation and Disposal

Sludge is an unavoidable waste that results from all water treatment plants [41], and CWW treatment technologies are no exception. The amount of sludge and the rate of sludge generation for the CWW treatment depends on the type of technology being used. [10] reported an increase in sludge generation with an increased coagulant concentration with the addition of Na bentonite (clay mineral), slightly reducing its quantity. All the technologies reviewed in this study had some sludge generated from their processes.

Out of the 34 articles reviewed, 11 mentioned sludge production from their technologies, representing about one-third of the total articles. [40] reported a sludge volume of $0.4m^3$ after 20 weeks of operating their full-scale treatment system. Their produced sludge was accumulated in a sand bed and disposed of in a landfill. A hybrid Bio-MF treatment system by [2] also produced sludge that was removed every three days and disposed of without any treatment or reuse. The different processes combined by [18] to treat wastewater also had a significant sludge production, 12.5% of the wastewater was turned into sludge by coagulation. Additionally, ceramic ultrafiltration and reverse osmosis also had 20%, and 28% of their feed water turned into sludge, respectively.

The potential for sludge reuse will depend on its composition, and knowledge about its quantity and generation rate will also inform management measures. The composition of the sludge generated by [48] in their electrochemical treatment system was linked to the type of electrode used, Al electrode's sludge had hydroxide and oxyhydroxide ions while Iron electrode's sludge contained only oxyhydroxide ions. The sludge quantities were $11.6kg/m^3$ for the Aluminium electrode and $2.1kg/m^3$ for the Iron electrode. This was similar to the sludge produced by [26]. [24] in their study suggested the valorisation of their generated sludge by using it as an adsorbent due to its composition of ion complexes. Another characterisation was done to determine the morphology and constituent of sludge by [21]. They observed that the composition of the generated sludge was related to the adsorption of chemicals used in car washing and the dissolution of electrodes (Aluminium) used in their electrochemical process. Their sludge had an amorphous structure, and the main components were Al_3O_2, N and Ca.

3.3. Economic Analysis of CWW Treatment Systems

CWW treatment systems are designed to protect the environment from pollution, conserve water, and, most notably, the carwash operator, save costs from water-related bills. Therefore, installing a treatment system at a carwash station is seen to be environmentally friendly and financially beneficial. This is true when the system is efficient in removing pollutants and economically feasible to invest in. It has been reported by [33] that treating CWW can reduce freshwater usage and save up to 88% of freshwater. [40] also reported less than 40L of fresh water being used per carwash after recycling CWW. This translates to cost savings when the operator must buy water for operation and discharge wastewater into sewers (in countries where discharge into sewers is billed). Where the clean water comes from a well, the cost savings will be associated with the energy consumption for pumping the water [38]. There have also been reports of as high as 80% cost savings on water-related bills after installing a recycling system [49].

The capital cost, payback period, treatment efficiency of the treatment system collectively play a role in whether a car wash operator will be willing to invest in such a technology. The suitability of an investment is related to its payback period. In the carwash industry, the amount of water being recycled/saved per day (water demand) and the cost of water and or energy consumption is what significantly affects the payback period [39], [40]. Therefore, a shorter payback period is preferred over a longer one. The invested money will not be held up for so long with a short payback period. This makes it possible to invest in other ventures in the shortest possible time. From the articles reviewed, only a few (primarily full-scale treatment technologies) had cost estimations for their systems. Table 6 shows an economic evaluation of some of these technologies. The capital costs observed from this review ranged from US$187 to US$9,470. The cheapest CWWR technology was developed in India. This system comprised skimming, lime and soda addition, sedimentation, and filtration. Conversely, the most expensive CWWR technology was a Flocculation flotation and ozonation technology developed in Brazil. The total cost is closely related to the treatment technology; the addition of a single treatment method can significantly increase the overall total cost of the treatment system. This is observed in a study by [39] where ozonation was replaced with chlorination for deactivating pathogens found in CWW. The operational cost was reported to have increased significantly due to high energy consumption by the ozonation process. Annual operational and maintenance costs also ranged between about US$2000 and US$3000. In terms of payback period, the literature reviewed in this study reported up to a payback period of 140months, with the least payback period being five months. Generally, a shorter payback period is acceptable for carwash operators to ensure that their investments yield the needed returns in no time.

Carwash wastewater recycling technologies included in this study can save up to $5000m^3$ of freshwater annually and save carwash operations more than US$20,000 annually. The combination of coagulation, sedimentation and sand filtration provides the highest water savings, while Flocculation flotation and ozonation/chlorination, although relatively expensive, provide the highest annual returns (Table 6).

Table 6. Economic Evaluation of carwash treatment technologies

Technology	Cost-Benefit		Amount of water saved (m^3/year)*	Amount of Money saved (US$/year)	Reference
	Cost of system (US$)	Payback Period (months)			
Sedimentation coagulation and sand filtration	2,677 – capital cost 1,865 – annual operational cost	7.5 if cost of water is US$2/$m^3$ 15 months if cost of water is US$1/$m^3$	3600	3600 to 7200	[37]
Coagulation Sedimentation and Sand Filtration	8,049	-	5054	-	[36]
Rotating Biological Contactor, granular filtration, and membrane ultrafiltration	-	-	1747	6522	[38]
Flocculation flotation and ozonation (FFO)	9,470 – capital cost 2,796 – annual operational and maintenance cost	up to 140	1747	4992-20,196	[39]
Flocculation flotation and Chlorination (FFC)	7,929 – capital cost 2,122 – annual operational and maintenance cost	up to 100			
Skimming Sedimentation and Sand filtration	187	7	312	282	[3]
Flocculation column flotation, sand filtration and chlorination	4,542.00	5 - 50	2,496	-	[40]

*Where hourly water savings are reported in the original literature, it is assumed that; system is used for 8hours per day; 26 days per month; 12 months per year - value not reported

Table 7. Comparison of pros and cons of carwash technologies

Treatment technologies	Strengths	Weaknesses
Stand-alone Electrochemical processes	• High removal efficiency for turbidity (99%); oil and grease (100%); TSS (98%); Surfactants (99%); COD(97%); BOD (94%)	• High voltage is required to increase pollutant removal efficiency thereby increasing electricity consumption and hence the operational cost • Produces sludge in the process which requires treatment before disposal
Membrane filtration	• High removal efficiency for TSS (100%); turbidity (99%) COD (99%) • Can achieve a high permeate quality with a small area • No chemicals are required for operation	• High capital cost • Membrane flux can reduce significantly over a short time • Poor performance in reducing TDS, EC • Membrane fouling can be reduced by using a pre-treatment step which increases capital and operational expenditure • Need for treatment of concentrate produced
Biological treatment	• Highly effective in removing surfactants (100%) • The system is simple to operate • Low construction costs • Low energy consumption and hence operational cost • No chemicals required for operation	• Treatment efficiency depends on hydraulic retention time thereby could require large land area for full-scale applications • Requires additional treatment steps to produce reusable carwash wastewater
Combined technologies Coagulation pre-treatment step with membrane filtration	• Highly efficient in reducing turbidity (99.9%); suspended solids (100%) and COD (96%) removal	• Higher operational cost due to constant demand for coagulants • High capital cost associated with membrane filtration • Produces sludge in the process which requires treatment before disposal
Sedimentation, flotation with membrane filtration and reverse osmosis	• Highly efficient in reducing turbidity (100%), TDS (82%), TSS (91%), COD (81%) and oil-grease (90%) • No chemicals required for clarification	• High capital cost associated with membrane filtration and reverse osmosis
Flocculation flotation sand filtration	• Good performance in the removal of (turbidity) 99% and COD 75%	• Poor performance in reducing TDS, EC anionic surfactants • Needs additional treatment step to handle coliform removal • Needs constant supply of chemicals • Relatively lower capital and operational cost • Produces sludge in the process which requires treatment before disposal

3.4. Strengths and Weaknesses of Carwash Wastewater Recycling Technologies

Table 7 presents the strengths and weaknesses of contemporary carwash wastewater recycling technologies based on literature. The table depicts clearly that, over the years, the ability of a carwash wastewater recycling technology to remove pollutants from the wastewater with high efficiency has been the primary focus of research. Therefore, literature is awash with studies reporting on the technical performance of technologies for recycling carwash wastewater, while the economic viability and the environmental impacts largely remain neglected. Even in developed countries where regulations demand that carwash stations install recycling technologies for their wastewater, the cost of the technology plays a crucial decision-making role in selecting the technology. Because, given two technologies that can achieve the same pollutant removal efficiency, it will be financially imprudent for a carwash station operator to go for the more expensive option. Particularly in countries where wastewater legislations do not exist or are poorly enforced, the added benefit of increasing profit margins from installing such technologies will be a compelling reason for carwash operators to switch to wastewater reuse. Hence, although a given technology may be highly efficient in removing pollutants from wastewater, the cost factor needs to be considered. Moreso, the environmental impact of these technologies needs to be put under the lenses of researchers. For instance, although membrane filters and reverse osmosis filters are highly efficient in removing pollutants from wastewater, there is eventually brine solution (concentrate) generated from these technologies that need to be treated before disposal (Table 7). Additionally, combined technologies that employ a coagulation/flocculation or electro-coagulation process usually produce sludge. This sludge results from the agglomeration of colloidal particles and becomes another source of environmental pollution if not treated and disposed of properly.

However, earlier studies employing these technologies to treat carwash wastewater have overlooked these aspects. Therefore, this study propounds that an acceptability score or rating must be developed for contemporary and future carwash wastewater recycling technologies, considering three major elements: pollutant removal efficiency, economic viability, and environmental protection. An ideal carwash wastewater technology must therefore fulfil these three requirements.

3.5. Areas for Further Research

This review has identified considerable gaps in the existing literature on carwash wastewater recycling technologies. First and foremost, many researchers have focused their lenses on the performance of the technologies in the removal of pollutants without considering other crucial aspects of the technologies they developed. At present, no cross-cutting research has been conducted to compare carwash wastewater recycling technologies vis-à-vis their performance, economic viability, and environmental impact. Therefore, future research will benefit from studies that compare these three fundamental aspects of carwash wastewater recycling technologies. Technologies developed in the future for carwash wastewater recycling must aim to fulfil these prerequisites: highly efficient in removing pollutants from carwash wastewater, have low capital and operational costs, have a short payback period, and do not pollute the environment in the process of recycling carwash wastewater. Secondly, this study has made it clear that combined treatment technologies are more effective than stand-alone treatment methods. However, the combination of stand-alone treatment technologies that checks all the acceptability requirements – performance, economic viability and environmental protection has not been examined. Further studies are needed in this area.

A comparison of coagulation methods to determine an effective but low-cost coagulant for treating carwash wastewater and implications on sludge characteristics in different contexts still needs to be studied in the future. The available literature is scanty. Such studies will reduce operational costs associated with treatment technologies that employ a coagulation treatment step. Moreover, there is the need to comprehensively assess the characteristics of by-products (concentrate or sludge) resulting from carwash wastewater recycling and develop methods to treat and either reuse or dispose of them safely.

4. Conclusions

This systematic review was conducted to critically examine the performance of the various treatment technologies for carwash wastewater, their sludge produced and economic aspects. Overall, the study reviewed 34 different research papers published over the past decade. Membrane processes, electrochemical methods and combined treatment methods were the most typical treatment technologies adopted for carwash wastewater treatment. Combined treatment technologies were the predominant method adopted for treating carwash wastewater. This was followed by membrane filtration and then electrochemical methods. Membrane filtration processes performed better at removing COD and turbidity than combined treatment methods. However, the major problems with using membranes to treat CWW are reducing flux over time and membrane fouling. Electrochemical treatment methods are also excellent at reducing oil grease colour and turbidity. However, their pollutant removal efficiencies tend to increase by increasing the voltage supplied. This increases energy consumption, which in turn increases the cost of operation.

Although all these treatment technologies inevitably produce sludge as a by-product of their treatment processes, this study found scant literature on the characteristics of the sludge produced and the disposal mechanisms for the sludge. Per the studies reviewed, between one-fifth and one-third of the feedwater (CWW) used in membrane processes turned to sludge, while up to 12kg/m^3 of sludge is produced for electrochemical treatment processes. For flocculation-flotation methods, 20L of sludge is produced weekly. The sludge contains hydroxide and oxyhydroxide ions and is mainly landfilled.

An analysis of the economic aspects of the CWWR technologies showed that the flocculation flotation and ozonation (FFO) process has the highest capital (about US$10,000) and annual O&M costs (about US$3000). The payback period and the cost savings of the CWWR technologies are heavily reliant on the unit cost of water. For the technologies assessed in this study, the payback period ranged between 5 and 140 months, saving up to 5000m^3 of freshwater annually and annual cost savings of more than US$20,000. This study provides a strong impetus for further investigations into the characteristics of sludge produced and extensive economic analysis of the technologies for recycling carwash wastewater. It is evident from this study that there has been a lot of focus on the performance of technologies for recycling wastewater in the carwash industry without focusing on technologies for reusing or safely managing the sludge produced. This study, therefore, argues that to reap the full benefits of wastewater recycling in the carwash industry, the technologies developed must also take care of the sludge/wastewater produced and be economically viable.

ACKNOWLEDGEMENTS

This study was funded by the Regional Centre for Energy and Environmental Sustainability (RCEES) in the University of Energy and Natural Resources (UENR), Ghana, supported by the World Bank.

Competing Interests

The authors declare no competing interests.

Supplementary Sheet

List of all Reviewed Articles

No.	Authors	Year	Title	Country
1.	Nagamani et al.	2020	A Cost Effective Membrane Integrated Process for the Treatment of Vehicle Wash Wastewater	India
2.	Viet et al.	2020	Automotive Wash Effluent Treatment Using Combined Processes of Coagulation/Flocculation/Sedimentation–Adsorption	Brazil
3.	Gõnder et al.	2020	An integrated electrocoagulation-nanofiltration process for carwash wastewater reuse	Turkey
4.	Moazzem et al.	2020	Application of enhanced membrane bioreactor (eMBR) for the reuse of carwash wastewater	Australia
5.	Naveed ul Hasan et al.	2019	A Low-Cost Wastewater Treatment Unit for Reducing the Usage of Fresh Water at Car Wash Stations in Pakistan	Pakistan
6.	Veréb et al.	2019	Purification of real car wash wastewater with complex coagulation/flocculation methods using polyaluminum chloride, polyelectrolyte, clay mineral and cationic surfactant	Hungary
7.	Monney et al.	2019	Treating waste with waste: the potential of synthesized alum from bauxite waste for treating car wash wastewater for reuse	Ghana
8.	Ahmad et al.	2018	Design of a car wash wastewater treatment process for local car wash stations	Pakistan
9.	Uçar	2018	Membrane processes for the reuse of car washing wastewater	Turkey
10.	Moazzem et al	2018	Performance of ceramic ultrafiltration and reverse osmosis membranes in treating car wash wastewater for reuse	Australia
11.	Ganiyu et al.	2018	Electrochemical advanced oxidation processes (EAOPs) as alternative treatment techniques for carwash wastewater reclamation	Brazil
12.	Subtil et al.	2017	Water reuse potential at heavy-duty vehicles washing facilities – The mass balance approach for conservative contaminants	Brazil
13.	Pinto et al.	2017	Carwash wastewater treatment by micro and ultrafiltration membranes: Effects of geometry, pore size, pressure difference and feed flow rate in transport properties	Brazil
14.	Mohammadi et al.	2017	Electrocoagulation process to Chemical and biological Oxygen Demand treatment from carwash grey water	Iran
15.	Mohammadi et al.	2017	Removal of turbidity and organic matter from car wash wastewater by electrocoagulation processes	Iran
16.	Gonder et al.	2017	Electrochemical treatment of carwash wastewater using FE and Al electrode: Techno-economic analysis and sludge characterisation	Turkey
17.	Rodriguez Boularte et al.	2016	Reuse of car wash wastewater by chemical coagulation and membrane bioreactor treatment processes	Australia
18.	Tamiazzo et al.	2015	Performance of a wall cascade constructed wetland treating surfactant polluted water	Italy
19.	Rubí-Juárez et al.	2015	A combined Electrocoagulation-Electrooxidation Process for Carwash Wastewater	Mexico

No.	Authors	Year	Title	Country
			Reclamation	
20.	Kiran et al.	2015	Influence of Bentonite in polymer membranes for effective treatment of car wash effluent to protect the ecosystem	India
21.	Etchepare et al.	2015	Application of flocculation-flotation followed by ozonation in vehicle wash wastewater treatment/ disinfection and water reclamation	Brazil
22.	El-Ashtoukhy et al.	2015	Treatment of real wastewater produced from mobile car wash station using electrocoagulation technique	Egypt
23.	Tony and Bedri	2014	Experimental Design of Photo-Fenton reactions for the treatment of car wash wastewater effluents by response surface methodological Analysis	Egypt
24.	Shete and Shinkar	2014	Use of Membrane to treat car wash wastewater	India
25.	Radin et al	2014	Efficiency of Using Commercial and Natural Coagulants in Treating car wash wastewater	Malaysia
26.	Murari	2014	Recycling and Reuse of carwash wastewater	India
27.	Zaneti et al.	2013	Car wash wastewater treatment and water reuse- a case study	Brazil
28.	Lau et al.	2013	Car Wash Industry in Malaysia: Treatment of car wash effluent using ultrafiltration and nanofiltration	Malaysia
29.	Abdelmoez et al.	2013	Treatment of wastewater contained with detergents and mineral oils using effective and scalable technology	Egypt
30.	Zaneti et al	2012	More environmentally friendly washes: water reclamation	Brazil
31.	Bazrafshan et al.	2012	Application of Combined chemical and electrocoagulation process for carwash wastewater treatment	Iran
32.	Zaneti et al.	2011	Carwash wastewater reclamation. Full-scale application and upcoming features	Brazil
33.	Hsu et al	2011	Reclamation of car washing wastewater by a hybrid system combining bio-carriers and non-woven membranes filtration	Taiwan
34.	Bhatti et al.	2011	Chemical oxidation of carwash industry wastewater as an effort to decrease water pollution	Pakistan

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