

Carwash wastewater treatment using the chemical processes

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ABSTRACT

The carwash is known as one of the most important urban services that brings about the production of huge volume of wastewater with high turbidity and high chemical oxygen demand (COD). Seasonal and carwash location features affect the quality of carwash wastewater. Various methods with special focus on chemical processes have been employed for carwash wastewater treatment and eliminating different pollutants from this wastewater of great concern for the environment. This review was conducted for identifying and comparing the efficiency of chemical processes for carwash wastewater treatment. To this aim, key words were identified and a search protocol was defined to search studies in three databases: Scopus, Web of Science, and PubMed. The results of this systematic review indicated that coagulation (66%) is the most common chemical processes for carwash wastewater treatment. Although chemical processes are able to reduce the turbidity and COD over 80%. Due to the characteristics of carwash wastewater, chemical processes are a necessary pretreatment for processes such as membrane technology. Rapid treatment and high efficiency are the advantages of wastewater treatment by chemical methods, but the energy consumption and sludge volume are two main factors in selection the chemical processes for carwash wastewater treatment.

Key words: carwash wastewater, chemical process, coagulation, electrochemistry, wastewater treatment

HIGHLIGHTS

- Considering the qualitative properties of carwash wastewater, the use of chemical processes requires pretreatment steps such as filtration and aeration.
- Given the importance of suspended solids and turbidity in carwash wastewater, the coagulation process is the predominant chemical process employed in the studies (65%) for carwash wastewater treatment.

INTRODUCTION

Annually, millions of motor vehicles are registered all over the world; there is a need for these to be frequently washed by commercial car wash services. The water requirement for each washing varies according to the type of car, season, level of pollution and type of washing, but it is mentioned that water requirement for automatic washing of each car is estimated to be 200 liters (Rodriguez Boluarte *et al.* 2016). In addition, it is estimated that more than 10 cubic meters water is consumed per day at one carwash station (Bhatti *et al.* 2011). Therefore, the carwash is considered as one of the most important urban water uses; carwash wastewater (CWW) is one of the most common types of wastewater in the communities. Carwash wastewater contains a significant concentration of different pollutants such as surfactants, phosphorus, nitrogen, solids, organic matter, and oil contents (Bhatti *et al.* 2011; El-Ashtoukhy *et al.* 2015; Rodriguez Boluarte *et al.* 2016; Gönder *et al.* 2017; Magnago *et al.* 2018; Moazzem *et al.* 2018; Monney *et al.* 2019). In various studies, different qualities have been reported for CWW (Han *et al.* 2018; Magnago *et al.* 2018), which can be as a result of the impact of the carwash location and the type of vehicle being washed (Al-Gheethi *et al.* 2016). For instance, CWW in rural areas can be more turbid than urban

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areas; sand and clay are higher in these areas on the surface and tires of the car. As well, in the cold seasons, there is a possibility of increased turbidity in the CWW (Rodriguez Boluarte *et al.* 2016).

As a consequence of large volume of CWW with a wide spectrum of pollutants of most concern, various processes such as chemical coagulation and filtration are being used for treatment this wastewater, which seriously threaten the environment (Bhatti *et al.* 2011). Chemical processes such as coagulation have been used to treat various types of wastewater, including textile wastewater and brewery wastewater, and this method has been proven to have a good efficiency for reduction the pollutants found in CWW (Rodriguez Boluarte *et al.* 2016). Therefore, the chemical processes are used as primary methods for treating CWW (El-Ashtoukhy *et al.* 2015). Treatment of CWW for reuse purposes is possible by using processes such as membrane technology (Torkashvand *et al.* 2021), but due to the limitations of these methods for treatment of wastewaters with high oil and turbidity, chemical processes have an important application in pretreatment of CWW. So, in recent years, chemical processes have also been considered as an important part of the treatment system for the reclamation and reuse of CWW (Panizza & Cerisola 2010a; Moazzem *et al.* 2018; Medel *et al.* 2019). Electrochemical processes have recently received great attention by researchers as a promising technology for CWW treatment (Gönder *et al.* 2017; Ganiyu *et al.* 2018; Han *et al.* 2018; Magnago *et al.* 2018).

To date, no review of such studies has been published in the academic literature or elsewhere; there is no available comprehensive source of information on (1) what chemical processes have been considered for CWW treatment, (2) what are the results of these chemical technologies in terms of reduction pollutants present in CWW. In this systematic review, the authors attempted to study the chemical processes used for CWW treatment and also to determine the operation aspect and parameters affecting the efficiency of these processes in reducing the CWW pollutants.

METHOD

Literature search

This systematic study was carried out with key word identification and defining a search protocol for extracting articles from three scientific databases: Scopus, Web of Science, and PubMed. The search strategy was performed using the protocol based on the existence of the word: carwash and either one of the words: wastewater, effluent, and water in the title, abstract or throughout the article. After completing the search in the databases, duplicate examples were removed from the list of found articles and the remaining articles were screened for further selection and final articles.

Eligibility criteria

The final articles were selected based on the eligibility criteria; the authors exclusively focused on studies that investigated a chemical process for CWW treatment. Accordingly, the authors selected all studies that (1) focused on the CWW treatment, (2) investigated chemical treatment alone or combined with other technologies (e.g. membrane technology), (3) investigated efficiencies and affecting factors on chemical processes for CWW treatment.

Selection of studies

All authors conducted an independent and blinded screening of the literature according to the criteria provided above. After the initial screening of titles, the authors selected 62 studies (Figure 1). In the first step, articles in the English language were extracted from the found articles and the next steps of screening were performed consistent with the aim of current systematic review. Afterwards, the articles in which chemical processes for CWW treatment were referenced in abstract were extracted. Finally, in the third stage, the contents of the articles were studied and 29 articles with focus on efficiencies and conditions affecting the chemical processes for CWW treatment were selected.

Data extraction

Data from fully eligible studies were extracted. The authors extracted the following data from the content of the eligible articles: (1) quality characteristics of CWW which be treated by a chemical process, (2) type of chemical process used for treatment, (3) pretreatment methods or post-treatment in CWW treatment by chemical process, (4) efficiency of chemical processes in CWW treatment, and (5) operation condition and remarks for in CWW treatment by chemical process such as sludge volume and chemical dosage. A schematic diagram of the search protocol and screening strategy is presented in Figure 1.

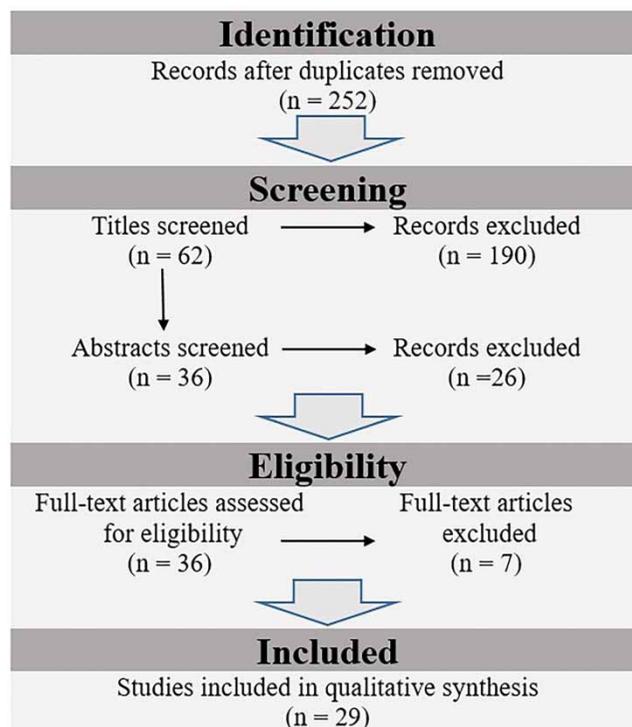


Figure 1 | Flow diagram of study identification.

LITERATURE REVIEW

The selected papers for the present systematic study, which mostly focused on chemical processes as the main treatment or a part of CWW treatment approaches, were published after 2004. Finally, the 29 most relevant published papers focusing on chemical processes for CWW treatment with a wide range of pollutants were selected. However, more attention should be paid to treatment of CWW containing significant concentrations of contaminants such as nutrients, organics, particulate matter, oil, grease, diesel detergents and sand.

The chemical processes employed in the found papers for CWW treatment were mainly divided into coagulation methods, and oxidation in some cases. [Figure 2](#) provides an overview of different chemical processes used in the selected articles as either the main or complementary methods for CWW treatment.

As summarized in [Table 1](#). The efficiency of chemical processes in removal of CWW pollutants was reported to be high. For instance, a 80% removal efficiency were reported for turbidity and COD in CWW ([Magnago et al. 2018](#); [Monney et al. 2019](#)).

RESULTS AND DISCUSSION

Overview of publications

The search strategy and protocol definition for selecting literature described in the method section of this paper generated a list of publications: selected peer-reviewed papers describing different chemical processes for CWW treatment (See [Table 1](#)). The following subsections describe and discuss some content of the publications. Most publications deal with Coagulation (10 articles), Electrocoagulation (10 article), Electro-oxidation (6 articles), Chemical oxidation (4 articles), respectively.

Coagulation

As shown in [Figure 2](#), 46% of selected studies employed chemical coagulation processes for CWW treatment. The high utilization of the coagulation process in the CWW treatment was likely to be due to extensive qualitative characteristics of CWW: turbidity (128–1,000 NTU) ([Bhatti et al. 2011](#); [Chu et al. 2012](#); [El-Ashtoukhy et al. 2015](#); [Al-Gheethi et al. 2016](#); [Rodriguez Boluarte et al. 2016](#); [Moazzem et al. 2018](#)), total solids (4,200–5,800 mg/L) ([Bhatti et al. 2011](#); [Rodriguez Boluarte et al. 2016](#)) and surfactants (95 mg/dm³) ([Panizza & Cerisola 2010a, 2010b](#)) in CWW, inspiring the researchers and authorities to

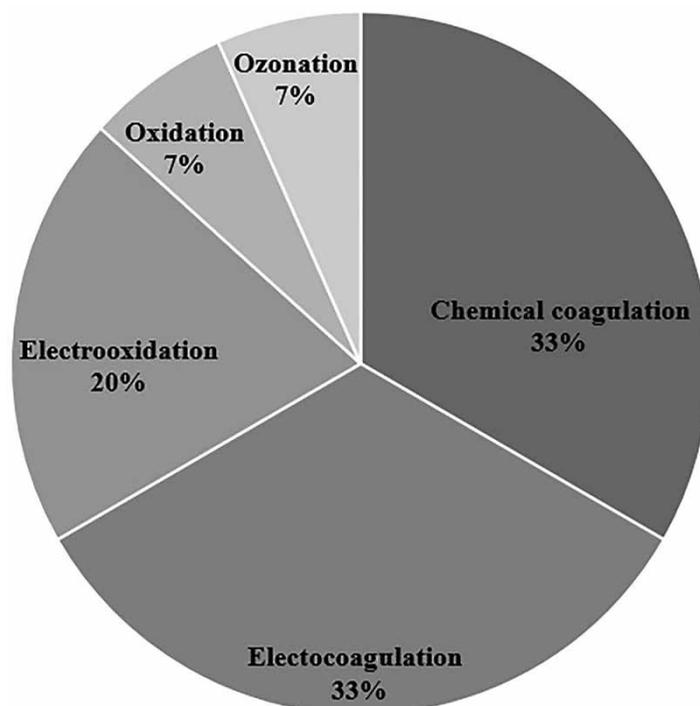


Figure 2 | A summary illustration of various chemical processes used for carwash wastewater treatment.

consider coagulation as a common method for CWW treatment or as pretreatment for CWW (Medel *et al.* 2019). In addition, as shown in Table 1, in some cases a good efficiency was reported as the main reason for using the coagulation process in CWW treatment. Alum has the ability to reduce COD in CWW; increasing the alum dose accordingly decreased the COD. Bhatti *et al.* (2011) reported that the use of 80 mg/L alum led to the reduction of COD by 93.3% when initial COD influent was 1,019 mg/L. By increasing the dosage of alum (Bhatti *et al.* 2011) and other coagulants (Al-Gheethi *et al.* 2016), the reduction of turbidity will increase; alum with a concentration of 80 mg/L decreased the turbidity by 96% (Bhatti *et al.* 2011). At the low dosage of coagulant, the main mechanism to reduce turbidity is attributed to solids destabilization, while trapping is the main mechanism for reducing the turbidity of the CWW when high dosages of coagulant are employed (Bhatti *et al.* 2011). Furthermore, using multi-blended coagulants which take advantages of alum, bentonite, and soluble polymers, due to the production of larger flocs, causes more COD and turbidity reduction in comparison with alum (Wharton *et al.* 2004).

Many studies reported that the use of other coagulants such as ferrous sulfate (Gönder *et al.* 2017), polyaluminum chloride (Tang *et al.* 2007; Tan & Tang 2008; Rodriguez Boluarte *et al.* 2016), FeCl_3 (Tang *et al.* 2007; Moazzem *et al.* 2018) and polyaluminum ferric chloride (PAFC) (Zhang *et al.* 2012) can be useful in CWW treatment, however, the efficiency of these coagulants varies. For example, Tang *et al.* (2007) reported that the efficiency for COD reduction by 25 mg/L polyferric sulfate (PFS) and polyaluminum chloride (PAC) was determined to be higher than that for FeCl_3 , however, at the dosage of 40 mg/L, FeCl_3 had better COD reduction compared with PFS. The reason for the high removal of COD is likely to be due to inherent characteristics of PAC coagulant: high absorption of organic matter with a negative charge on the PAC flocs with a positive charge (Rodriguez Boluarte *et al.* 2016). In addition, (Moazzem *et al.* 2018) showed that 45 mg/L of ferric chloride as coagulant has a better effect on the reduction of turbidity compared with alum coagulant.

To improve the efficiency of the coagulation process in CWW treatment, advanced coagulation and co-coagulants have received much attention by researchers. For example, Tang and co-workers (Tang *et al.* 2007; Tan & Tang 2008) reported that the use of 1 to 1.5 mg/L of KMnO_4 as advanced coagulation before adding coagulant reduced turbidity by 5 mg/L due to the strong oxidation potential of this material on organic matter and the possibility of its hydrolysis to MnO_2 , which has absorbent, oxidizing and packing effects. Furthermore, adding KMnO_4 before the coagulant can reduce its effectiveness for flocs destruction and improve process efficiency in comparison with adding KMnO_4 after coagulant addition.

Table 1 | The chemical properties of carwash wastewater after use of chemical processes for wastewater treatment

Treatment process	Influent characteristics	Results	Year	References
Coagulation (alum) + Ozonation	pH = 8.5, SS (mg/L) = 4,200, Turbidity (NTU) = 1,000, COD (mg/L) = 433, TN (mg/L) = 11.73, TP (mg/L) = 25	pH = 7.3, SS (mg/L) = 9, Turbidity (NTU) = 3.7, COD (mg/L) = 141, TN (mg/L) = 2.6, TP (mg/L) = 0.4	2016	Rodriguez Boluarte <i>et al.</i> (2016)
Coagulation with 105 mg/L FeSO ₄ ·7H ₂ O.	pH = 6.96, Turbidity (NTU) = 275.1, COD (mg/L) = 220, DO (mg/L) = 2.55	pH = 4.13, Turbidity (NTU) = 18.8, COD (mg/L) = 180, DO (mg/L) = 6.78	2016	Al-Gheethi <i>et al.</i> (2016)
Coagulation with 45 mg/L FeCl ₃	pH = 6.42, Turbidity (NTU) = 522, COD (mg/L) = 295, TDS (mg/L) = 259	pH = 4.5, COD (mg/L) = 100, TDS (mg/L) = 400	2017	Moazzem <i>et al.</i> (2018)
Aeration + coagulation with Al ₂ (SO ₄) ₃ ·16H ₂ O + oxidation with H ₂ O ₂	pH = 8.75, TS (mg/L) = 5,855, Turbidity (NTU) = 772, COD (mg/L) = 1,019, Oil (mg/L) = 83.7	pH = 7.5, TS (mg/L) = 538, Turbidity (NTU) = 43, COD (mg/L) = 70, Oil (mg/L) = 3.1	2010	Bhatti <i>et al.</i> (2011)
Electrocoagulation	Turbidity (NTU) = 128.7, COD (mg/L) = 155	COD reduction = 69% Turbidity reduction = 96%	2012	Chu <i>et al.</i> (2012)
Electrocoagulation	Turbidity (NTU) = 386, COD (mg/L) = 566	Turbidity (NTU) < 50, COD (mg/L) < 100	2015	El-Ashtoukhy <i>et al.</i> (2015)
Electrocoagulation (Al electrode)	pH = 8, Chloride (mg/L) = 150, COD (mg/L) = 560, Oil (mg/L) = 125	pH = 6, Chloride removal (%) = 33, COD removal (%) = 88, Oil removal (%) = 68	2017	Gönder <i>et al.</i> (2017)
Electrocoagulation (Fe electrode)	pH = 8, Chloride (mg/L) = 150, COD (mg/L) = 560, Oil (mg/L) = 125	pH = 8, Chloride removal (%) = 50, COD removal (%) = 88, Oil removal (%) = 90	2017	Gönder <i>et al.</i> (2017)
Electro-oxidation (lead dioxide (PbO ₂) anode)	pH = 6.4, Surfactant (mg/dm ³) = 95.5, COD (mg/dm ³) = 572, BOD (mg/dm ³) = 178	pH = 8.9, Surfactant reduction after 10 h >95%, COD reduction after 10 h = 99%	2009	Panizza & Cerisola (2010b)
Electro-oxidation (boron-doped diamond (BDD) anode)	pH = 6.4, Surfactant (mg/dm ³) = 95.5, COD (mg/dm ³) = 572, BOD (mg/dm ³) = 178,	pH = 8.9, Surfactant reduction after 3 h = 100% %, COD reduction after 3 h = 100%	2009	Panizza & Cerisola (2010b)
Electrocoagulation (Fe electrode + Electro-oxidation with BDD anode)	pH = 6.4, Surfactant (mg/dm ³) = 95.5, COD (mg/dm ³) = 572, BOD (mg/dm ³) = 178	Surfactant after Electrocoagulation (mg/dm ³) = 0, COD reduction after treatment (1.5 h) = 97%	2009	Panizza & Cerisola (2010a)
Fenton + photo-Fenton	Surfactant (mg/L) = 2.1 Oil and Grease (mg/L) = 112.3 COD (mg/L) = 201.4	Surfactant (mg/L) = 0 Oil and Grease (mg/L) = 1.2 COD (mg/L) = 12.3	2018	Magnago <i>et al.</i> (2018)

(Tang *et al.* 2007; Tan & Tang 2008). Zhang *et al.* (2012) showed that combination of polyacrylamide (PAM) (0.75 mg/L) and PAFC (150 mg/L) had the best treatment efficiency in CWW containing 5–15 mg/L oil.

As shown in Table 1, the coagulation process with abilities to reduce both the turbidity and COD can also be effective in treatment of other parameters of CWW. For example, the use of the coagulation process due to the presence of flocs with positive charges has a good effect on the removal of phosphorus from CWW (Rodriguez Boluarte *et al.* 2016; Moazzem *et al.* 2018). However, the use of alum and ferric chloride can lead to an increase in TDS in the effluent (Bhatti *et al.* 2011; Moazzem *et al.* 2018), which is most likely attributable to the presence of charged free ions originated from coagulant hydrolysis (Bhatti *et al.* 2011). In addition, the use of some coagulants such as FeCl₃ led to a severe decrease in the pH of the wastewater (Al-Gheethi *et al.* 2016). This phenomenon was similarly observed for other coagulants such as alum but in less severity (Bhatti *et al.* 2011), and can aid in the selection of better coagulants from the view point of reuse purposes. Financial aspect and the presence of color in sewage can also be considered as important criteria for choosing coagulants for CWW treatment; Tang *et al.* (2007) suggested PACs instead of FeCl₃ for CWW treatment due to lower prices and the presence of lesser color in the effluent.

Electrocoagulation

In addition to chemical coagulation, the electrocoagulation processes can also be used in CWW treatment (Panizza & Cerisola 2010a; Chu *et al.* 2012; El-Ashtoukhy *et al.* 2015). The use of iron and aluminum electrodes in the electrocoagulation process for CWW treatment was investigated in many studies (Panizza & Cerisola 2010a; Chu *et al.* 2012; El-Ashtoukhy *et al.* 2015; Gönder *et al.* 2017) and the results indicated that the efficiency of this process depends mainly upon the conditions of operation (current density, operating time, and conductivity) and the characteristics of the electrolyte (wastewater) (El-Ashtoukhy *et al.* 2015; Gönder *et al.* 2017). The efficiency of the electrocoagulation process to reduce surfactant (100%), COD (>94%), turbidity (>60%) and oily materials from CWW was reported to be high and considerable (Panizza & Cerisola 2010a; Chu *et al.* 2012).

The current intensity is an important factor on the efficiency of the electrocoagulation process in reducing wastewater pollutants (Chu *et al.* 2012; Gönder *et al.* 2017). As the current intensity increases, the process efficiency increases because voltage changes accordingly to influence coagulant dosage rate, bubble production rate and floc growth rate (Chu *et al.* 2012; Gönder *et al.* 2017). For instance, Gönder and colleagues (Gönder *et al.* 2017) studied the role of current density in the electrocoagulation process for removal of oil and grease with two electrodes (Al and Fe). They reported that increases in the current density from 0.1 to 1 mA in Al electrode electrocoagulation process led to increases in the removal of oil and grease from 30 to 65%. However, this removal efficiency for the Fe electrode electrocoagulation process was reported to be between 74 and 85%. Of note, COD removal efficiency for Al electrode and Fe electrode electrocoagulation processes were 75–85% and 77–84%, respectively (Gönder *et al.* 2017). Furthermore, (Chu *et al.* 2012) reported that increases in current density from 0.3 to 1.5 mA in the Al electrode electrocoagulation process increased the turbidity and COD removal efficiency from 75 to 95% and from 25 to 50%, respectively.

In the Al anode electrocoagulation process, increases in current intensity led to increasing the dissolution of Al⁺³ so increasing the alumina hydroxide precipitate. In addition, increasing the production of bubbles in the cathode area, which improves the mixing of pollutants and aluminum hydroxide, promoted the removal efficiency of COD (El-Ashtoukhy *et al.* 2015). As well, increasing the current intensity led to increases in efficiency of CWW treatment in electrocoagulation processes with iron as the electrode due to increasing the dissolution of iron and the production of iron precipitate (Panizza & Cerisola 2010a). However, excessive increases in the current intensity can lead to an increase in bubble sizes, which consequently results in an adverse effect on COD reduction; smaller bubbles have a greater surface area to absorb particles and form larger flocs (Chu *et al.* 2012).

The ratio of soluble organic matter to suspended organic matter in CWW is an effective parameter in reducing the COD through the electrocoagulation processes. Although electrocoagulation is an effective process to reduce surfactant and oil content, soluble organic material in CWW cannot be coagulated and trapped well in flocs and removed from CWW in this process. Therefore, part of the COD caused by the soluble materials will not be reduced in the electrocoagulation process (Panizza & Cerisola 2010a). This phenomenon leads to lower and gradual slowing of COD reduction a short time after the start of the process, and eventually continues to be stable. For instance, the results of research conducted by Panizza & Cerisola (2010a) showed that reduction of COD at the start of processes was quickly eliminated by 58% after 2 minutes; the COD reduction process slowed down after 10 minutes and finally COD in effluent was reported to be 150 mg/L (Panizza & Cerisola 2010a). In addition, increasing the conductivity of CWW can be effective in improving the treatment efficiency;

increases the concentration of chloride ion and the higher ability of chloride ions destroyed the passive oxide film on the anode surface, which prevents metal dissolution and electron transfer (El-Ashtoukhy *et al.* 2015). pH changes affected the efficiency of the electrocoagulation process in CWW treatment and the best efficiency was observed at neutral and near acidic pH (Chu *et al.* 2012; El-Ashtoukhy *et al.* 2015). At low pH, Al^{+3} is the predominant ion in the solution and reduces the process efficiency, however, at pH 5–9, $\text{Al}(\text{OH})_3$, $\text{Al}(\text{OH})^{+2}$, $\text{Al}_2(\text{OH})^{+4}$, and $\text{Al}_{17}(\text{OH})_{32}^{+7}$ are generated due to hydrolysis and polymerization of Al^{+3} . Furthermore, at high pH, the dominant form of aluminum is $\text{Al}(\text{OH})_4^-$ which is not known as a coagulant, therefore, the efficiency will loss (Chu *et al.* 2012; El-Ashtoukhy *et al.* 2015). In the iron-anode electrocoagulation process, iron hydroxide compounds like $\text{Fe}(\text{OH})_3/\text{FeOOH}$ are formed more when the pH is 8–9 (Gönder *et al.* 2017). Furthermore, at pH 7, the increase in iron hydroxide concentration and the oxidation of this ion led to a reduction in the COD removal efficiency due to decreases in the production of the iron ion from the anode (Panizza & Cerisola 2010a). According to these issues mentioned above pH = 6 and pH = 7–8 were reported to be the optimal pH for the Al electrode and the Fe electrode electrocoagulation processes, respectively (Chu *et al.* 2012; Gönder *et al.* 2017) and an electrode pH 7–8 was reported (Panizza & Cerisola 2010a; Gönder *et al.* 2017).

In addition to the characteristics of CWW, operational conditions such as treatment time, electrode distance and temperature also played an important role in the efficiency of CWW treatment through electrocoagulation (Chu *et al.* 2012; El-Ashtoukhy *et al.* 2015; Gönder *et al.* 2017). Although the temperature can affect the electrocoagulation process in many ways including rate of reaction, metal hydroxides solubility, liquid conductivity, and kinetics of gas bubbles or small colloidal particles, however, it was reported (El-Ashtoukhy *et al.* 2015) that temperature changes between 30 and 45 °C did not have a significant effect on the process efficiency. By increasing the electrode distances in the electrocoagulation processes, the efficiency of the CWW treatment will increase due to higher over-potential generated by the concentration polarization, and in addition, the distance of the small electrodes prevents a large number of bubbles escaping, and affecting the energy transfer in the electrolysis process (Chu *et al.* 2012).

Increasing the treatment time in constant current intensity leads to improvement in the purification efficiency through increasing metal dissolution and its hydrolysis polymerization (Chu *et al.* 2012; Gönder *et al.* 2017). The type of the electrode also has an important effect on the efficiency of the electrocoagulation process for CWW treatment; the aluminum electrode for this purpose was much better than the iron electrode, because Fe^{+2} which are dissolved from the iron electrode in the electrolyte is not strong coagulant and requires oxygen to be converted to Fe^{+3} , which is a better coagulant. Also, components following Al^{+3} hydrolysis such as $\text{Al}(\text{H}_2\text{O})_6^{+3}$ and $[\text{Al}(\text{H}_2\text{O})_4(\text{OH})_2]^+$ have a much better absorption capacity compared with components from Fe^{+3} hydrolysis (El-Ashtoukhy *et al.* 2015).

The operational conditions may vary depending on the type of process selected for CWW treatment. For example, in electrocoagulation, increasing the process pH improved the process of coagulation due to the production of more polyvalent ions and metal hydroxyl formation. While, increasing current density and time increased the COD removal efficiency in the electrocoagulation process (Emamjomeh *et al.* 2019). Amongst the optimal conditions for CWW treatment, stirring speed should be taken into account, because increasing it is useful as long as it leads to the uniformity of wastewater, increases in ion transfer from electrodes to fluid and the formation of larger flocs in the electrocoagulation process. However, if the stirring speed exceeds a certain limit, it will lead to disintegration of the flocs and consequently the filtration efficiency decreased. For this reason, Gönder *et al.* (2019) reported that increasing the stirring speed from 150 to 250 rpm increased the treatment efficiency of CWW using electrocoagulation, while further speeds up to 350 rpm decreased the treatment efficiency (Gönder *et al.* 2019). For temperature in CWW treatment using the electrocoagulation process, it has been determined that increasing the temperature due to increasing electrical conductivity and decreasing fluid viscosity reduced energy consumption and reduced treatment costs. While increasing temperature increased the solubility of metal hydroxide deposits and therefore decreased the removal efficiency. Therefore, by adjusting the treatment temperature, this effect should be considered; Gönder *et al.* (2020) due to the higher efficiency, despite a slight increase in energy consumption, preferred a temperature of 25° C to 45° C for treatment under optimal conditions (Gönder *et al.* 2020).

Electro-oxidation process

The electro-oxidation process is an electrochemical process that has drawn much attention by researchers for CWW treatment (Panizza & Cerisola 2010a, 2010b). Panizza & Cerisola (2010a, 2010b) reported that use of Pb as anode for about 10 hours completed the COD reduction at an initial concentration of 572 mg/L. This process, similar to electrocoagulation, is affected by current density. Increasing the current density due to more production of radical hydroxyl increased the

removal efficiency (Panizza & Cerisola 2010b). The electro-oxidation process efficiency is largely affected by CWW quality parameters. For instance, Panizza & Cerisola (2010a, 2010b) reported that the effect of detergents in CWW and its scum lowered the COD reduction rate in the PbO_2 -electrode electro-oxidation process. Also, the type of anode employed for the electro-oxidation process will affect the process efficiency. For example, one group (Panizza & Cerisola 2010a, 2010b) reported that a boron-doped diamond (BDD) anode was much faster and more completely reduced COD compared with a lead anode (PbO_2) due to the high reactivity of hydroxyl radicals electro-generated by the BDD anode. In addition, the electro-oxidation process increased the pH at both anodes; the production of carbonate due to the conversion of organic matter to carbon dioxide changed the pH from 6.4 to 8.9 (Panizza & Cerisola 2010b).

Many studies indicated that in the electrochemical processes, after a certain time from the beginning of the treatment process, the desired efficiency is achieved; further contact time increases in efficiency is either negligible or constant as time proceeded. These conditions are true for electrochemical processes in the treatment of CWW. Therefore, the further time and current densities after achieving a desired efficiency can be ignored. The optimum point can vary depending on the characteristics of the carwash effluent. Atiyah and Abdul-Majeed employed an electrochemical method with aluminum electrode after 30 minutes and voltages of 10 volts for CWW treatment with COD 632 mg/L, turbidity 227 NTu, TDS 403 mg/L and oil content equal to 105 mg/L. They achieved 90% COD and turbidity reduction after 30 min with voltages of 10 volts. However, increasing further treatment time and voltage led to negligible variation in removal efficiency (Atiyah & Abdul-Majeed 2019). Although exceeding the optimal treatment point can slightly increase the efficiency, however, it greatly increases the treatment costs and, in terms of economics and ease of operation, it is better to define the treatment model at the optimal point. A suitable solution to achieve higher treatment efficiency in terms of flow intensity and time spent at the optimal point is the use of auxiliary processes in the chemical treatment of CWW. This experience has been seen in the use of ultrasonic processes to improve the efficiency of wastewater treatment by electrochemical methods (Moulood & Abdul-Majeed 2019).

The efficiency of the electro-oxidation processes in CWW treatment depends on the operational factors and optimal conditions; achieving the desired efficiency in the minimum time and minimum energy consumption is very effective. For example, the role of pH in the efficiency of CWW treatment efficiency using the electro-Fenton reaction is very effective because this factor directly affects the production of hydroxyl radicals. At high pH, Fe^{2+} is deposited and, at pH less than 2, hydrogen peroxide cannot decomposes into hydroxyl radicals, so the pH in using for using electro-Fenton process for CWW treatment should be higher than 2 and in the acidic state (Davarnejad *et al.* 2019). The current density is also directly related to the increase in COD removal efficiency, because further regeneration leads to ferrous ion and accordingly increases in the production of hydroxyl radicals, however, from one point onwards the increase in current may decrease the efficiency due to competitive reactions (Davarnejad *et al.* 2019). In the electro-Fenton process for CWW treatment, an increase in COD removal efficiency is obtained by increasing the $\text{H}_2\text{O}_2/\text{Fe}^{2+}$ ratio, however if excess H_2O_2 is present, this leads to the conversion of hydroxyl radicals to a weaker hydroxyl radical through oxidation (Davarnejad *et al.* 2019).

Chemical oxidation

The importance of reducing the turbidity of CWW has led to extensive application of various coagulation methods such as chemical coagulants for CWW treatment. The use of coagulants alone may not be effective in carwash effluent. In this case, the use of synthetic polymers and materials such as bentonite can be beneficial. For example, Veréb *et al.* (2019) reported a 98% reduction in the turbidity of CWW in the application of 20 mg/L polyaluminum chloride, 100 mg/L Na-bentonite and 0.5 mg/L anionic polyelectrolyte. The use of this chemical compound also reduced COD by 59% and extractable oil by 85% (Veréb *et al.* 2019).

The use of chemical oxidation in combination with other chemical processes have a beneficial effect on the reduction of CWW pollutant (Bhatti *et al.* 2011; Rodriguez Boluarte *et al.* 2016). Ozonation has been proven to have good influence on the reduction of organic matter present in CWW due to the reaction of organic matter with the ozone molecule and the reaction of radical hydroxide produced during the ozonation process with organic matter (Rodriguez Boluarte *et al.* 2016). Ozonation also can dramatically reduce color in CWW. One group (Rodriguez Boluarte *et al.* 2016) reported that coagulation and flocculation process changed the CWW color from black to pink, and accordingly after ozonation, there was no clear color. Also, using 2.5–3 mL/L H_2O_2 (40%) was recognized as an appropriate solution to improve the quality of effluent after coagulation with the alum (Bhatti *et al.* 2011).

Integrated processes

Considering the processes presented in Table 1, in some cases, researchers have tried to apply chemical processes as a combined process for CWW treatment. Due to the diversity of CWW contaminants, it was better to use an integrated method for its treatment. Research has shown that chemical methods, especially the coagulation and oxidation process, play an essential role in most combined CWW treatment methods (Sarmadi *et al.* 2020). However, the characteristics of wastewater and the ability of each treatment method makes it efficient to use an integrated system to achieve the desired efficiency. As an example, Durna & Nevim (2021) reported the 84% reduction efficiency of COD when using the combined process of microwave + persulfate + electrocoagulation versus the 64% reduction efficiency of COD when using the combined process of ozone + persulfate + electrocoagulation for the same wastewater. Selecting the appropriate integrated method based on recognizing the characteristics of wastewater and the capability of chemical treatment methods, in addition to achieving appropriate efficiency can also be effective in reducing treatment costs. Durna and Nevim stated that the use of ozone instead of electrocoagulation in the combined process with microwave + persulfate, increased the cost of wastewater treatment by 0.04 euros per liter, and reduced the efficiency from 84 to 61% (Durna & Nevim 2021).

The main reasons for combining different processes are to either reduce the energy consumption or improve the CWW treatment (Panizza & Cerisola 2010a; Rodriguez Boluarte *et al.* 2016). For example, the use of a BDD-anode electro-oxidation process with current intensity of 10 mA at 1.5 hours after electrocoagulation (6 minutes) could considerably reduce the COD (97%), which would accordingly reduce energy consumption (96.8%) (Panizza & Cerisola 2010a). Furthermore, in the research, the combination of the ultrasound process with electrocoagulation would increase the efficiency of COD removal from CWW because ultrasound causes regeneration of a new electrode surface by cavitations and/or micro-streaming effect (Chu *et al.* 2012). Ultrasound also prevents covering the surface with bubbles; however, ultrasound has an adverse effect on reducing the turbidity by separating the pollutant from the aluminum hydroxide colloids and returning them to the solution (Chu *et al.* 2012). This group reported that the ultrasound process alone had a 12 and 14% removal efficiency for COD and turbidity from CWW. Although membrane methods have been found to be effective in reducing the turbidity of carwash effluent in combination with various coagulation processes (Torkashvand *et al.* 2021), the use of methods such as sedimentation and filtration in combination with coagulation can also reduce energy costs while maintaining the same efficiency (Emamjomeh *et al.* 2019). Also, in some cases, the combination of processes can eliminate the adverse changes in effluent resulting from the use of a process. For example, the result of one research study stated that the addition of alum in CWW treatment reduced effluent pH from 8.75 to about 7.2 and by adding hydrogen peroxide to pH changed to 7.5 (Bhatti *et al.* 2011).

The use of chemicals for CWW treatment is considered as one of the main stages of hybrid systems because turbidity is one of the most important properties of CWW, and must be reduced before treatment of CWW with other treatment methods such as membrane methods. In addition, using electrochemistry in CWW treatment can be useful in reducing the treatment time. Based on these conditions, the proposed methods for on-site treatment of CWW with the aim of reuse need great attention regarding electrochemical processes and the use of coagulants as pretreatment, or one of the main parts of treatment, for this type of wastewater (Torkashvand *et al.* 2020).

Other processes

In addition to chemical processes, other processes have been used for CWW treatment. Membrane processes are the most widely used method for this purpose. Also, other processes such as sedimentation and filtration have also been used in the CWW treatment as a pretreatment (Uçar 2018). The characteristics of chemical treatment and the appropriate ability of other methods such as the membrane processes have led to the use of integrated processes at different stages of CWW treatment in many studies to achieve better efficiency (Tang *et al.* 2007; Jiku *et al.* 2013; Istirokhatun *et al.* 2015; Moazzem *et al.* 2018). An important point in comparing chemical processes with the membrane process as the two most widely used methods in CWW treatment is treatment purposes. For example, reuse is a serious goal in CWW treatment. In achieving it, each of the chemical and membrane processes has utilities and limitations in terms of treatment efficiency and consumption standards, water recovery rate, operating conditions, and also financial conditions.

Types of membrane processes such as nanofilter, microfilter, ultrafilter and reverse osmosis are highly treatment efficient in reducing solids to 100% (Moazzem *et al.* 2018) oil and grease more than 78% (Istirokhatun *et al.* 2015), turbidity 90 to 100% (Lau *et al.* 2013; Istirokhatun *et al.* 2015; Moazzem *et al.* 2018), and COD 70 to 95% (Lau *et al.* 2013; Istirokhatun *et al.* 2015; Moazzem *et al.* 2018), which may be higher in some cases than chemical processes. However, they have important limitations

compared to chemical processes. Studies have shown a significant increase in retentate that permeates membrane processes used in CWW treatment (Moazzem *et al.* 2018), while a severe and rapid flux reduction has been observed when using various types of membranes in CWW treatment (Boussu *et al.* 2007; Lau *et al.* 2013; Istirokhatun *et al.* 2015; Kiran *et al.* 2015; Uçar 2018). These two limitations are important in terms of effluent quantity. Changes in effluent quality such as pH reduction due to the rejection of soluble ions and the passage of soluble gases such as CO₂ by some type of membrane, are other limitations for membranes in CWW treatment (Moazzem *et al.* 2018).

CONCLUSION

The application of chemical processes for carwash wastewater treatment was reviewed. Considering the qualitative properties of carwash wastewater, the use of chemical processes requires pretreatment steps such as filtration and aeration. Given the importance of suspended solids and turbidity in carwash wastewater, the coagulation process was the predominant chemical processes employed in the studies (65%) for carwash wastewater treatment. In addition, some coagulants increased TDS and reduced pH in the effluent, which can be considered a weakness for reuse purposes. The use of electrochemical processes over a shorter time resulted in high efficiency in the removal of carwash wastewater pollutant, but an important consideration in these processes was the need to reduce energy consumption. The combination of electrocoagulation and electro-oxidation processes was highly successful for carwash wastewater treatment over a short time and with the least energy consumption. Finding methods and coagulants that give the least sludge production, less adverse changes in the effluent quality, plus reducing the treatment time, reducing energy consumption, and finding integrated methods with higher efficiencies and higher water recovery rates would be more attractive for carwash wastewater treatment in the future.

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CONFLICTS OF INTEREST

The authors of this article declare that they have no conflict of interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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