Next Scientists
EUROPEAN INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND MANAGEMENT STUDIES

TYPE Original Research
PAGE NO. 28-40
DOI 10.55640/eijmrms-05-10-05

Check for updates

Technologies For Car Wash Wastewater Treatment: A 2015–2025 Literature Review

OPEN ACCESS

SUBMITED 31 August 2025
ACCEPTED 26 September 2025
PUBLISHED 31 October 2025
VOLUME Vol.05 Issue10 2025

Murtazaev Farkhod Azgaralievich

Ph.D. student, Samarkand state architecture and construction university, Uzbekistan

Yakubov Kutfidin Asliyevich

Prof. v.b., Ph.D. (Tech.), Associate Professor, Samarkand state architecture and construction university, Uzbekistan

Abstract: Car wash wastewater contains surfactants, oils, suspended solids, heavy metals, and microbial pollutants. Discharge wastewater from carwash facilities poses serious environmental risks, and high-water use leads to resource depletion. This literature review synthesizes research published between 2015 and 2025 on technologies developed for car wash wastewater treatment. The review is based on a systematic analysis of peer-reviewed studies selected from the Scopus database in accordance with PRISMA guidelines, resulting in 38 articles addressing various treatment approaches. The findings are organized thematically across biological processes, membrane filtration systems, adsorption techniques, electrocoagulation, advanced oxidation processes, hydrodynamic cavitation, and integrated hybrid systems. Electrocoagulation emerges as a particularly promising technology due to its broad-spectrum removal capabilities, operational simplicity, and compatibility with other methods. Membrane filtration, especially ultrafiltration and nanofiltration, consistently achieves high-quality effluent suitable for reuse but requires effective pretreatment to mitigate fouling. Biological treatments offer strong performance for biodegradable pollutants, while advanced oxidation and cavitation techniques address persistent organics and surfactants. The review highlights that hybrid (combined) treatment systems, which strategically combine multiple processes, provide the most comprehensive and resilient solutions for pollutant removal and water reuse. Despite considerable progress, research gaps remain regarding energy efficiency, long-term system performance, and cost optimization. The findings underscore the necessity of developing scalable, sustainable treatment configurations to ensure safe discharge and promote water reuse in the car wash industry.

Keywords: Car wash wastewater; Wastewater treatment; Electrocoagulation; Membrane filtration; Biological treatment; Hybrid treatment systems; Water reuse.

Introduction: Car wash wastewater (CWW) is a complex effluent containing a mixture of organic and inorganic pollutants, including oils and grease (O&G), suspended solids, surfactants, heavy metals, nutrients, and microbes. A single vehicle wash can consume 100–400 liters of water and mobilize contaminants like brake dust, road grime, lubricants, and detergents. Studies have shown that without treatment, discharge from car wash facilities can far exceed environmental limits, for instance, COD levels up to 1400 mg/L and surfactants 54 mg/L (over 50 times legal limits in some cases) have been reported. Such untreated discharges pose serious risks to aquatic ecosystems and public health, contributing to water pollution and bacterial spread. These concerns, coupled with growing water scarcity, have spurred extensive research into effective treatment and recycling of car wash wastewater.

This review examines recent advances (2015–2025) in technologies for treating car wash wastewater, with a particular focus on electrocoagulation (EC) as a promising method alongside biological, filtration, adsorption, oxidation, and hybrid approaches. The aim is to synthesize findings from the past decade, compare treatment efficiencies and limitations, and identify trends and knowledge gaps in this field. It was targeted studies from 2015–2025 to capture the latest developments and intensifying research interest in sustainable water reuse at vehicle wash facilities.

METHODOLOGY

Was conducted a comprehensive literature search of the Scopus database for 2015–2025, limited to Environmental Science and Engineering subject areas. The search combined keywords related to car wash wastewater and treatment methods (e.g., “car wash wastewater treatment”, “physicochemical treatment”, “biological treatment”, “water reuse”). This yielded 377 publications for initial screening. Then applied PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to filter relevant studies. The inclusion criteria and exclusion criteria were as follows:

- Inclusion: Peer-reviewed journal articles (in English) focused on car wash wastewater treatment technologies or reuse, with full-text available.

- Exclusion: Studies not specific to car wash wastewater, papers lacking technical or experimental data, conference abstracts, review articles without new data, and non-scientific reports.

After screening, 38 articles were selected for in-depth analysis. These form the basis of this review, providing insight into various treatment methods’ performance, applicability, and limitations in the car wash context. The selection emphasizes research progress over the last decade, as evidenced by an increasing number of publications in this period.

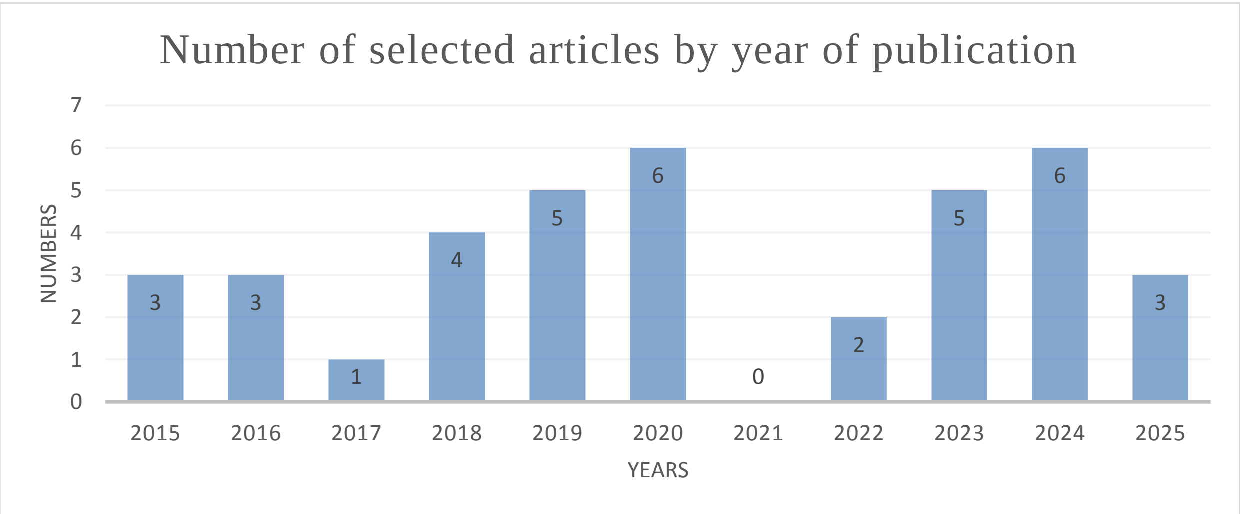

Figure 1: Annual publications on car wash wastewater treatment (2015–2025) based on Scopus-indexed studies. A clear rising trend is seen, with notable peaks in 2020 and 2024 (6 publications each) and low output in 2017 and 2022. This reflects growing research attention to car wash wastewater issues in response to water scarcity and stricter environmental regulations.

Geographically, research contributions came from around the globe. Europe and Asia feature prominently, led by Poland (9 studies) and Malaysia (5), with significant input from Iran (4) and Australia (3). Other countries including China, India, Egypt, Brazil, and Turkey contributed additional studies, underscoring the worldwide interest in improving car wash wastewater management.

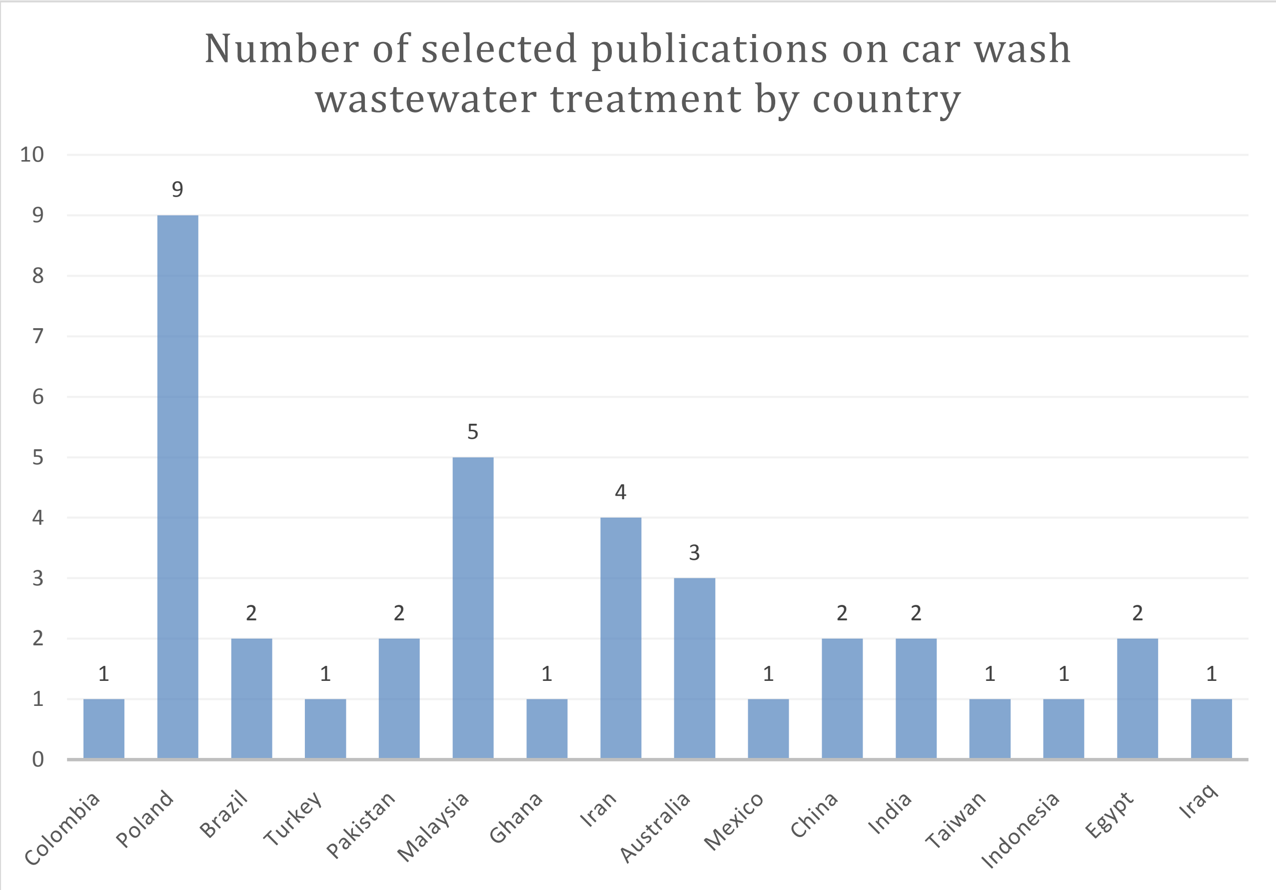

Figure 2: Top contributing countries in car wash wastewater treatment publications (2015–2025). Poland produced the most studies (9), followed by Malaysia (5), Iran (4), and Australia (3). The remaining publications were distributed among numerous other countries (e.g., China, India, Egypt), reflecting broad global engagement.

In the selected literature, a wide array of treatment technologies has been investigated to address the complex pollutant mix in car wash effluents. Figure 3 shows the distribution of methods studied, highlighting a trend toward hybrid systems that combine multiple treatment processes, and a strong emphasis on membrane filtration (especially ultrafiltration) and electrocoagulation among recent studies. Biological treatments, adsorption techniques, conventional filtration (sand/granular media), and advanced oxidation processes (AOPs) like Fenton's reagent and ozonation have also been explored, often in conjunction with one another. This review is organized thematically by treatment method. First it was discussed each major category biological, membrane, adsorption, electrocoagulation, advanced oxidation (including special cases like hydrodynamic cavitation) outlining their operating principles, reported performance in removing key pollutants, advantages and limitations. Then it was considered hybrid systems that integrate multiple methods, as these have shown particularly high effectiveness. Finally, it was concluded with an overview of technology trends, the most promising solutions (with an emphasis on electrocoagulation), and future research needs such as optimizing energy use and system integration.

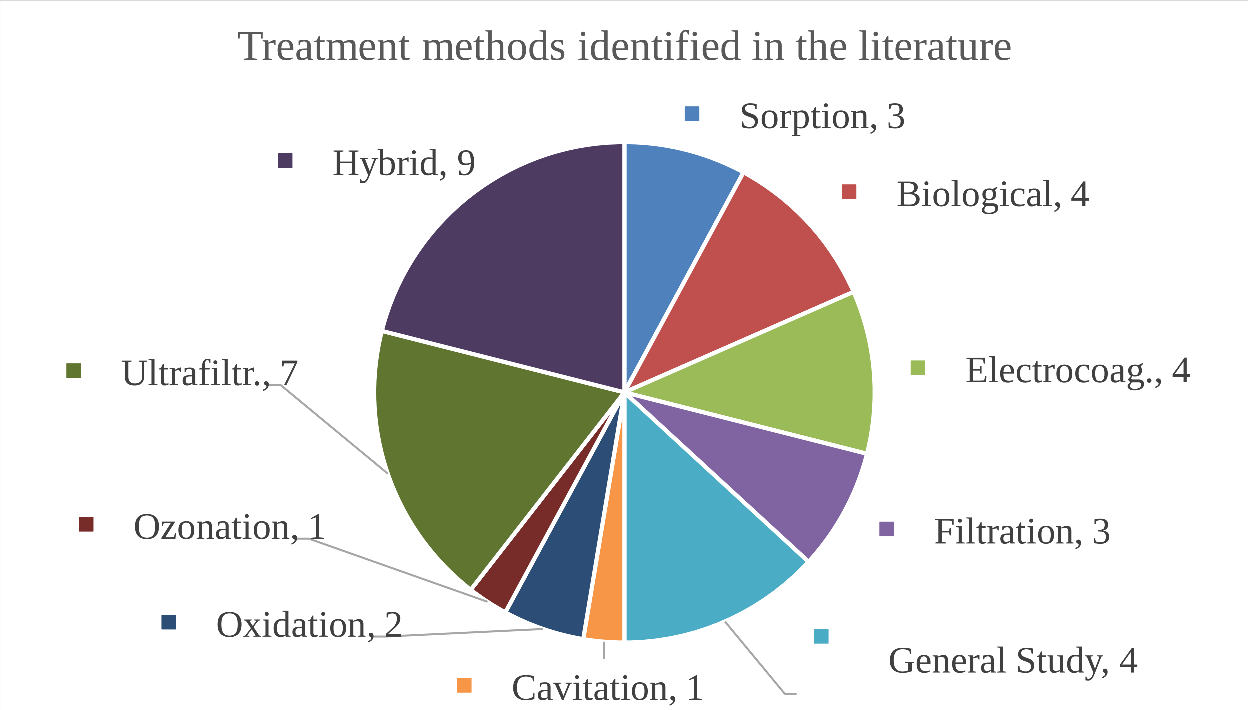

Figure 3: Distribution of treatment methods examined in car wash wastewater studies (2015–2025). Integrated hybrid systems (combining processes) were most common (9 studies), followed by ultrafiltration (UF) membrane processes (7). Biological treatments, electrocoagulation (EC), and general system design studies each appeared in 4 publications. Adsorption and media filtration methods were present in 3 studies each, while oxidation processes (e.g., Fenton, ozonation) and hydrodynamic cavitation were less frequently studied.

Biological treatment methods

Biological treatment techniques harness microorganisms to biodegrade pollutants and have shown good potential for car wash wastewater, especially for removing biodegradable organics (e.g. oils, surfactants) and nutrients. Common biological systems studied include Up flow Anaerobic Sludge Blanket (UASB) reactors, membrane bioreactors (MBR) (and enhanced MBRs with added features), and moving bed biofilm reactors (MBBR). These systems vary in configuration (anaerobic vs aerobic, suspended vs attached growth), but all rely on microbial communities to metabolize contaminants.

Several recent studies highlight the performance of such systems. (Maqbool et al., 2019) used a lab-scale UASB reactor and found that adding a specialized hydrocarbon-degrading bacterial culture (bioaugmentation) dramatically improved removal efficiency – achieving ~96% COD and ~97% oil/grease removal, versus 80% and 74% respectively without bioaugmentation. The UASB also produced biogas (over 2 m³ per kg COD removed), illustrating an added energy recovery benefit. Operating conditions were mild (20–28 °C, neutral pH), indicating feasibility under ambient conditions.

An advanced enhanced MBR (eMBR) system was studied by (Moazzem et al., 2020), who treated 100% real car wash wastewater over 17 months in a multi-stage bioreactor with anaerobic, anoxic, aerobic zones, a hollow-fiber ultrafiltration membrane, and continuous UV disinfection. Under optimized conditions (hydraulic retention time ~209 hours, flux ~6 L/m²·h, moderate MLSS ~300 mg/L), the eMBR achieved ≥99.8% COD removal and virtually complete elimination of turbidity, surfactants, and E. coli, meeting stringent reuse standards for water quality. This demonstrates that MBRs can produce effluent clean enough for direct recycling when properly designed and operated, albeit at the cost of long retention times and careful control to prevent membrane fouling.

A MBBR system was investigated by (Włodyka-Bergier et al., 2023) , using various moving media carriers in an aerated tank treating raw car wash wastewater. At an optimal retention time of 20 hours, the best-performing media (Mutag BioChip) attained 66% COD removal, ~73% BOD_5 removal, and notably high turbidity (94%) and color (90%) reduction. While the COD removal was moderate (likely due to non-biodegradable components), the substantial turbidity and particulate reductions show the efficacy of biofilm systems for solids and colloids. The authors noted that additional pretreatment would be needed to meet full reuse standards, but the MBBR can serve as a robust secondary treatment step.

Advantages: Biological processes can effectively degrade a broad range of organic pollutants and surfactants through metabolic processes. They produce less chemical sludge compared to physicochemical treatments and can be cost-efficient, especially when energy can be recovered (e.g., biogas from anaerobic digestion). MBRs and similar systems also provide consistent pathogen removal when coupled with membrane filtration or disinfection.

Limitations: Their performance strongly depends on wastewater biodegradability and operating conditions (pH, temperature). Car wash effluent often contains recalcitrant chemicals (e.g., certain surfactants, hydrocarbons, heavy metals) that are not easily biodegraded. Long hydraulic retention times may be required for high removal, and biomass can be inhibited by shocks of high pollutant concentration or toxic components. Additionally, maintenance of bio-systems (e.g., preventing membrane fouling in MBRs, managing biofilm carriers) adds complexity. Thus, biological treatment alone may not suffice for complete treatment of car wash wastewater, but it is very useful as part of a multi-stage process.

Membrane filtration methods

Membrane filtration methods including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) have been extensively applied to polish wastewater due to their ability to physically separate contaminants. In car wash wastewater treatment, membranes are valued for producing high-quality effluent (suitable for reuse) by removing suspended solids, colloids, and even dissolved substances (depending on pore size). However, they often require pretreatment to prevent fouling and can struggle with high loads of oil and organics.

Several studies demonstrate the performance of membrane-based treatments. (Uçar, 2018) implemented a multi-barrier system combining settling, sand filtration, and sequential UF/NF on real car wash effluent in Turkey. After a 1-hour settling and coarse filtration pretreatment, the NF270 nanofilter (300 Da cutoff) achieved ~98% COD removal and complete phosphate elimination, as well as near-total removal of color and turbidity. The permeate met high water quality standards, and the addition of powdered activated carbon and $FeCl_3$ coagulant to the NF concentrate further improved overall COD reduction by ~60–76%. This underscores that combining chemical adsorption/coagulation with membrane steps can significantly enhance contaminant removal and mitigate fouling.

In contrast, (Hu et al., 2022) explored an innovative cyclonic microfiltration system in Taiwan that emphasizes fouling reduction and high throughput. Using a 1 µm polypropylene filter in a tangential (cross-flow) cyclonic setup, they directly filtered car wash water without pretreatment. The system obtained moderate reductions in COD (~43%) and surfactants (~45%), but was quite effective for suspended solids (81%) and O&G (66%) removal. Impressively, the flux was about 15,000 $L/m^2 \cdot h$, an order of magnitude higher than typical UF/NF, due to the centrifugal flow design minimizing membrane fouling. This suggests that novel MF configurations can handle the high solids and oil content of car wash wastewater with less clogging, though as a trade-off, they provide only partial removal of dissolved organics.

Membrane techniques have also been combined with other low-cost media. (Latha et al., 2023), for example, examined natural fiber filters (sugarcane bagasse and sawdust) as a pre-filtration step alongside alum coagulation. In column experiments, these bio-based filters achieved >90% COD removal and ~94% O&G removal at optimal depths (9 cm) and coagulant doses, nearly matching the performance of alum alone. Such approaches can act as a roughing filter before fine membranes or as part of decentralized systems, reducing the burden on expensive membranes by taking out the bulk of pollutants.

Advantages: Membrane processes can produce very high-quality effluent, removing turbidity, microbes, and even salts (in RO). UF and NF are particularly effective for car wash water reuse, as they can eliminate most colloids and a large fraction of COD (often >90% with NF), ensuring compliance with reuse standards. They are modular and can be installed in limited space (e.g., at a car wash site). Membrane systems reliably remove pathogens and are less sensitive to toxic spikes (since separation is physical).

Limitations: Fouling by oil, grease, and fine particles is a major issue – car wash effluent's high suspended and emulsified oil content can clog membranes quickly. This necessitates effective pretreatment (sedimentation, sand filters, coagulants) and/or frequent cleaning, which increases operational cost. Membranes (especially NF/RO) have high pressure requirements and energy usage, and generate a concentrated brine or sludge that requires disposal. The capital cost of membranes and their limited lifespan are also concerns for widespread adoption. Therefore, membranes are often best used as a polishing step in combination with other treatments rather than a standalone solution in this context.

Adsorption

Adsorption involves removing contaminants by binding them onto porous solid materials (adsorbents). While not as commonly applied alone for car wash wastewater, adsorption is increasingly used as part of multi-stage systems to target specific pollutants like residual oils, dyes, or surfactants. It can be cost-effective if low-cost or waste materials are used as adsorbents.

Recent studies have explored both natural and engineered adsorbents. (Ibrahim & Hashim, 2018) tested kapok fiber, a natural plant fiber with hydrophobic properties, to remove oil and surfactant from synthetic car wash wastewater. In simple batch trials, a small dose of kapok (0.1 g/150 mL) achieved complete (100%) removal of oil in just 10 minutes, while a larger dose (3 g) removed ~46% of an anionic surfactant (SDS). The excellent oil removal reflects kapok's oleophilic character, although surfactant uptake was more limited, likely due to kapok's low affinity for polar contaminants.

A study by (Rosli et al., 2020) (summarized in [3]) used a macrocomposite media composed of aggregates, zeolite, activated carbon, cement, and sand in a fixed-bed column to treat real car wash effluent in Malaysia. At an optimal flow (10 mL/min), the composite filter achieved very high removal efficiencies: up to ~98.5% COD and 98.4% suspended solids, albeit at a short contact time (2 minutes) in the column. This suggests that a well-designed mixture of adsorptive and filtrative media can polish water effectively if the flow rate allows sufficient contact.

Another adsorbent investigation by (Saad et al., 2024) examined activated carbon from coconut shells (CSAC) in batch mode for car wash wastewater. With optimized conditions (0.8 g/100 mL, pH 7, ~1–2-hour contact), the coconut-based carbon removed about 91% of COD and 88% of BOD, and substantially reduced heavy metals (e.g., Zn by 68%, Fe by 86%). Activated carbon's broad-spectrum adsorption capacity makes it effective for both organic and inorganic pollutants, although it is relatively expensive.

Advantages: Adsorption is a simple, proven technology that can achieve high removal for specific pollutants. It is especially effective for oil/grease and certain organics – as seen with kapok fiber's complete oil removal. Adsorbents can be natural, low-cost materials (fibers, zeolites, charcoal) making the process economically attractive and suitable for small or decentralized operations. It is easy to operate (no complex controls or energy input, except perhaps pumping water through a column) and can be quickly implemented.

Limitations: Adsorption alone may not handle the entire load of car wash wastewater, because the capacity of adsorbents is finite and they can be quickly exhausted by high contaminant concentrations. Spent adsorbents require regeneration or disposal, potentially transferring pollution to another medium. Performance can also be sensitive to water chemistry (pH, presence of competing substances). Typically, adsorption is used as one stage in a treatment train – for example, after coagulation or biological treatment – to catch remaining contaminants. By itself, it might not reduce COD or nutrients to acceptable levels unless the influent was lightly polluted to begin with.

Electrocoagulation

EC is an electrochemical process in which an applied electric current dissolves sacrificial metal electrode (usually aluminum or iron) to release coagulant ions in situ. These metal ions hydrolyze to form metal hydroxide flocs that can adsorb and destabilize contaminants, similar to chemical coagulants but without added chemicals. Simultaneously, electrolytic gas bubbles (H_2) generated at the cathode aid in flotation of flocculated matter. EC has gained attention for car wash wastewater due to its simplicity and effectiveness in removing a wide range of pollutants (turbidity, oils, organics, heavy metals) in one step.

Mechanism in brief: At the anode, metal dissolves (e.g., $Al \rightarrow Al^{3+} + 3e^-$), while at the cathode water is reduced ($2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^-$). The generated Al^{3+} or Fe^{2+}/Fe^{3+} ions react with OH^- to form amorphous $Al(OH)_3$ or $Fe(OH)_x$ flocs. These flocs adsorb pollutants or enmesh suspended particles, which can then be separated via sedimentation or flotation. No external chemical coagulant is needed other than the electrodes themselves.

Multiple studies from 2015–2024 have demonstrated EC's high efficacy for car wash effluents. (El-Ashtoukhy et al., 2015) used a batch EC reactor with a spiral aluminum anode and flat aluminum cathode treating actual car wash water in Egypt. Under optimal conditions (current density ~11.7 mA/cm^2, pH 8, 14 min electrolysis), they achieved ~95% COD removal and 98% turbidity removal. Energy consumption was reported between 2.3–15 kWh per kg COD removed depending on conditions, indicating room for improving energy efficiency.

A study by (Medel et al., 2019) tested an iron electrode EC system (with carbon steel plates) and observed similarly high solids removal – 98.7% TSS and 98.3% turbidity in 15 minutes at a modest current density of 8 mA/cm^2, pH ~8.4. Color was reduced by ~93%, though dissolved organics (TOC) only by ~28%, suggesting that not all COD was accessible to EC in that case. The primary removal mechanisms were flocculation by Fe(OH)_n and some oxidative chlorine species generated, without needing additional oxidants.

Material and parameter optimization has been a theme in recent EC research. (Hoseinzadeh et al., 2024) compared different electrode materials stainless steel (SS304), galvanized iron (GI), and aluminum at varying pH (6–10) and current densities. They found α-Aluminum electrodes at acidic pH (~6) and high current (30 mA/cm²) yielded the best overall results, up to 97.5% COD and 98.5% turbidity removal after 2 hours. However, the stainless-steel electrodes, while slightly less effective in pollutant removal, consumed less energy and electrode mass, pointing to a cost-efficiency tradeoff. (Mohammadi et al., 2017), likewise, experimented with Al–Al, Fe–Fe, and hybrid Al–Fe setups, noting that iron electrodes excel at COD reduction (94% removal at pH 3), whereas aluminum is superior for turbidity (99.6% at pH 7). These findings illustrate that EC performance is highly tunable: electrode choice, current input, pH, and reaction time can be optimized based on the primary contaminants of concern (e.g., maximizing oil and turbidity removal vs. maximizing organic degradation).

Notably, electrocoagulation has been successfully integrated into hybrid treatment trains as both pretreatment and intermediate steps. For example, (Emamjomeh et al., 2019) combined EC (aluminum electrodes) with sedimentation and sand–carbon filtration, achieving ~95% removal of COD, anionic surfactants (MBAS), and turbidity – essentially a complete treatment sequence with EC as the key step. This hybrid approach takes advantage of EC's ability to reduce pollutant loads and improve subsequent filtration performance.

Advantages: EC can rapidly achieve high removal efficiencies for suspended solids, colloids, turbidity, and emulsified oils (often >95%). It also significantly reduces COD and BOD (commonly 70–97% depending on conditions) by coagulating organic matter. The process is relatively simple to operate (controlling voltage/current) and typically requires only electricity and basic electrodes, avoiding the handling of large volumes of chemical reagents. Sludge produced tends to be dewaterable and may be less voluminous than chemical sludge. EC is especially attractive for car wash facilities because of its compact footprint and on-demand operation (units can be turned on only when wastewater is generated).

Limitations: The energy consumption can be a concern, particularly if high currents or long electrolysis times are needed (optimizing current density is crucial to minimize kWh per volume treated). Electrodes are sacrificial and must be periodically cleaned (to remove passivating oxide layers) and replaced as they corrode, which incurs costs. The effectiveness of EC can be reduced in very low conductivity water or if certain pollutants (e.g. some surfactants) do not coagulate well with the metal hydroxides. Also, EC primarily transfers pollutants from liquid to a sludge phase, which still requires proper disposal or treatment. Lastly, while EC alone works well for many parameters, extremely stringent discharge or reuse criteria might still necessitate polishing steps (filtration, adsorption, or oxidation) to remove the last fractions of dissolved organics or nutrients. Despite these challenges, the consensus in the literature is that EC is one of the most promising single-unit operations for car wash wastewater, and its performance justifies its prominent role in integrated systems.

Advanced oxidation processes

AOPs involve generating highly reactive radicals (especially hydroxyl radicals •OH) to oxidize and break down recalcitrant organic pollutants that are not easily removed by conventional means. In car wash wastewater treatment, AOPs have been applied to target residual chemical oxygen demand (COD) and persistent surfactants in the water. Common AOP methods studied include Fenton and electro-Fenton reactions, ozonation, photocatalysis, and, in one case, hydrodynamic cavitation (discussed separately in the next section).

Electro-Fenton (EF) & Fered-Fenton: The Fenton process ($Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \bullet OH + OH^-$) produces hydroxyl radicals through the reaction of hydrogen peroxide with ferrous iron. In electro-Fenton, the ferrous ions and often H_2O_2 are generated in situ electrochemically (usually with an iron anode and a carbon-based cathode that facilitates H_2O_2 formation). (Davarnejad et al., 2019) applied an EF process to car wash wastewater and achieved significant removal of various pollutants under acidic conditions (optimal pH ~3). In under 1.3 hours of treatment, they reported ~69% COD reduction and ~74% anionic surfactant removal, along with improvements in BOD_5 and TSS. This indicates AOPs can substantially degrade the organic load and detergents present. Meanwhile, (Han et al., 2018) investigated a Fered-Fenton setup (an EF variant using a carbon felt cathode for enhanced H_2O_2 generation) on highly concentrated car wash water (COD >1500 mg/L, linear alkylbenzene sulfonate surfactants ~1479 mg/L). In 2 hours at 70 mA/cm² current, the system removed ~65% of COD and ~78.5% of LAS surfactant. However, it was noted that extended operation led to some cathode corrosion and formation of toxic by-products from the carbon electrode. These results demonstrate EF processes are effective for breaking down surfactants and improving biodegradability, but careful control (and material choices) is needed to avoid secondary contamination or diminished performance over time.

Ozonation: Ozone (O_3) is a strong oxidant that directly reacts with many organic compounds and also produces radicals in water. (Etchepare et al., 2015) evaluated a full-scale system in Brazil where ozonation was used as a final polishing step after flocculation, flotation, and sand filtration. In continuous operation (1 m^3/h flow, 10 m^3 ozone contact tank), the integrated process consistently achieved 96% COD reduction (from 683 to 96 mg/L) and eliminated >90% of surfactants and bacteria (E. coli) from the effluent. Ozone was effective in disinfecting and breaking down residual organics to meet local reuse standards. It's worth noting ozonation alone might not reach such high COD removal, but in tandem with preceding steps it can ensure thorough treatment. Ozone has the advantage of leaving no residual apart from oxygen, but it is energy-intensive to generate and must be handled carefully due to its reactivity.

Photocatalysis and others: While not highlighted in the core set of 38 studies, other AOPs like UV-photocatalysis or persulfate oxidation could be applicable. The focus in 2015–2025 literature, however, has been more on electrochemical AOPs and ozonation as described above.

Advantages: AOPs excel at degrading refractory and dissolved organic pollutants that survive other treatment stages. Surfactants, which are a major constituent of car wash waste, are particularly well-targeted by AOPs (the EF process removed ~70–80% of surfactants in studies). AOPs can also inactivate microbial contaminants and remove color/odor, improving the aesthetic and health quality of the water. They can significantly reduce COD and improve the biodegradability of the water, making subsequent biological treatment more effective if used as a pretreatment.

Limitations: Most AOPs are energy-intensive or require chemical inputs (H_2O_2, O_3, catalysts), which raises operational costs. They often work best in acidic pH (for Fenton), necessitating pH adjustment and later neutralization. Radical reactions may produce intermediate by-products that need careful monitoring; for instance, incomplete oxidation can yield smaller organic acids or even toxic compounds that need further treatment. With ozone, off-gas management is necessary to protect workers and the environment. Thus, AOPs are typically used in combination with other methods either as a polishing step for recalcitrant compounds or as a pre-treatment to break down pollutants and enhance overall removals.

Hydrodynamic cavitation

Hydrodynamic cavitation (HC) is a novel physical process where turbulent flow and pressure drop in a reactor induce the formation and violent collapse of microbubbles. The collapsing bubbles create localized high temperature and pressure micro-zones, leading to the generation of hydroxyl radicals and strong shear forces that can degrade pollutants, somewhat analogous to an AOP but without added chemicals. HC has been investigated as an emerging treatment for water containing hard-to-degrade substances like surfactants.

(Lebiocka et al., 2024) conducted a pilot study on car wash wastewater using a closed-loop 30 L cavitation system (steel orifice plate with multiple holes to create cavitation). They varied the inlet pressure (2–5 bar) and time (30–120 min) to optimize surfactant and COD removal. Under the best conditions identified (3 bar for 120 min), the HC process achieved up to 77% removal of anionic surfactants. Non-ionic surfactants were less affected (~35% removal) and COD reduction was limited to about 27% even at higher pressure. These results suggest HC is quite effective at breaking down certain surfactants (particularly the anionic type common in detergents), likely through radical and thermal effects during cavitation, but it is not as efficient in mineralizing bulk organic carbon (COD) on its own. The authors noted that while HC alone couldn't meet discharge standards for COD, its strength lies in being a chemical-free supplementary step that could be integrated with others. For example, HC pre-treatment could improve subsequent biodegradation or make coagulation more effective by altering colloids.

Advantages: Hydrodynamic cavitation requires only a pump and a specialized cavitation reactor (no chemicals), making it potentially low-cost to operate aside from electricity. It can degrade specific troublesome compounds like surfactants and also aids in disinfection to a degree (the extreme conditions can kill microbes). It's a scalable technology multiple cavitation units can be run in parallel for larger flows. Cavitation devices can also be combined with other AOPs (e.g., ozone or H_2O_2 injection) to enhance radical generation in a synergistic way.

Limitations: As a standalone treatment, HC may not achieve high removal of COD or other metrics beyond certain surfactant classes. It is more effective as part of a treatment train (either as pre-oxidation or polishing). Also, maintaining the conditions for cavitation (pressures of several bar, recirculation) consumes energy, and improper operation can cause damage (cavitation can erode surfaces). There is ongoing research to optimize cavitation reactor designs for maximum pollutant degradation. At present, HC is a promising but supplementary technology in car wash wastewater treatment, best coupled with traditional methods.

Hybrid and Integrated treatment systems

Hybrid systems combine two or more treatment processes to capitalize on their complementary strengths and achieve higher overall efficiency. Given the diverse contaminants in car wash wastewater, integrated approaches are often the most effective strategy, as no single method can remove all pollutant types to a high degree. The literature from 2015–2025 shows a clear trend toward such multi-stage systems, ranging from simple two-step processes to complex trains involving five or more-unit operations.

One illustrative example is the work of (Moazzem et al., 2018), who implemented a five-stage treatment train: coagulation, sedimentation, sand filtration, ceramic ultrafiltration, and reverse osmosis (RO). This comprehensive sequence achieved over 96% COD removal, 100% total nitrogen removal, and 99% turbidity reduction, producing an effluent meeting stringent Australian Class A reuse standards. The success lies in each stage tackling different fractions of the wastewater coagulation/flocculation removed bulk suspended matter and some organics, filtration and UF removed finer particulates and microbes, and RO polished dissolved salts and residual organics. Such high-end setups ensure maximum water recovery and quality, though at significant cost and complexity.

Another study by (Fayed et al., 2023) in Egypt used a more simplified hybrid approach combining physical and chemical steps. They employed a series of baffle tanks (for initial sedimentation), followed by a jar-test coagulation/flocculation with either alum or a natural humic acid polymer, then a settling tank. Despite being a low-tech setup, this approach achieved up to 97.6% COD removal and 99.5% O&G removal. Humic acid, a waste-derived coagulant, performed nearly as well as alum for organics removal, indicating sustainable alternatives are feasible. The multi-stage nature (baffle for grit/oil, coagulant for colloids, settling for separation) was key to these high removals even without advanced equipment.

Hybrid systems often integrate membranes with pretreatment. (Rodriguez Boluarte et al., 2016) combined chemical coagulation (using PAC or alum), ultrafiltration, and UV disinfection in a pilot plant. The pretreatment with coagulants yielded ~65% COD removal, and the UF+UV achieved 99.6% turbidity removal and complete E. coli disinfection. Without coagulation first, the membrane would likely foul and not reach such performance. Similarly, (Han et al., 2018) (the Fered-Fenton study) demonstrated that adding coagulation/flocculation (PAC/PAM chemicals) before a nanofiltration step significantly improved overall results – ~88% COD reduction and >65% surfactant removal, plus disinfection in the final water. These underscore the importance of pretreatment (like coagulation, EC, or bio) before tight membranes or AOPs, to extend their life and effectiveness.

Some hybrid systems target sustainability and cost reduction. (Al-Gheethi et al., 2016) integrated natural Moringa oleifera seed coagulant with an aerated bio-step and sand filtration in a simple four-stage lab setup. This achieved modest 35% COD removal but very high 97% turbidity reduction and complete oil removal impressive for a cheap, plant-based treatment. While COD was not fully treated, the system greatly improved clarity and removed most visible and floatable pollutants, making the water much less harmful. Such solutions are valuable for regions with resource constraints, as they use locally available materials and require minimal infrastructure.

In general, the combined evidence shows that hybrid systems can consistently attain >90% removal of major pollutants (COD, turbidity, surfactants, pathogens). By tackling the wastewater in stages physical separation, chemical coagulation, biological digestion, filtration, oxidation, etc. each pollutant class is effectively addressed. For instance, an integrated system might use sedimentation to remove grit and large particles, electrocoagulation to remove colloids and reduce COD, a biological reactor or constructed wetland to biodegrade organics, followed by sand filtration or membrane filtration to polish the water and remove remaining solids and microbes, and finally UV or ozonation to disinfect. Many such combinations have been tested, and the consensus is that no single process can achieve what a tailored combination can.

Advantages: Integrated systems deliver the highest treatment efficacy and reliability. They can be designed to meet strict reuse standards, allowing car wash facilities to recycle water and drastically cut freshwater consumption. Hybrid approaches also offer resilience: if one process is less effective for a certain pollutant or during a fluctuation in wastewater quality, the subsequent steps can compensate. By distributing the pollutant load, each component can operate under less stress (e.g., lower fouling rate on membranes, lower chemical dose needed after a bio-step). The synergy (e.g., EC reducing turbidity so that UV disinfection works better, or bio-treatment reducing organic load so RO fouling is less) leads to a more stable overall operation. Hybrid systems can also incorporate green technologies (like natural coagulants, biofilters) to improve sustainability.

Limitations: The complexity and cost are higher – multiple units mean higher capital investment, more maintenance, and the need for knowledgeable operation. Integrated systems might be overkill for small installations unless modular designs are implemented. There is also the challenge of coordinating the processes (ensuring, for example, that the flow rates and capacities of each stage match and that intermediate storage is provided if needed). Sludge and waste streams from multiple units (spent media, concentrated brine from RO, sludge from EC or coagulation) need holistic management. Nevertheless, for achieving near-complete purification and reuse of car wash wastewater, hybrid systems are unparalleled, and many researchers advocate their development and optimization as the path forward.

CONCLUSION

Car wash wastewater (CWW) is a high-strength, complex wastewater that cannot be safely discharged without adequate treatment. Over the past decade (2015–2025), research has produced a range of technologies to tackle the pollutants in CWW, and clear trends have emerged in the literature. Table 1 provides a summary comparison of the major treatment methods reviewed, highlighting their typical pollutant removal performance, advantages, and limitations.

Major Findings: Physico-chemical methods like electrocoagulation and coagulation-flocculation have proven extremely effective for rapidly removing turbidity, oils, and a large portion of COD. EC in particular stands out for its high removal efficiencies (often 90–97% COD/TSS reduction under optimal conditions) and its synergy when combined with other treatments. Membrane filtration (UF/NF/RO) reliably produces water clean enough for reuse (COD and turbidity removals >90%, complete pathogen removal), but is best used after other pretreatment steps to avoid fouling. Biological treatments like MBR and MBBR can achieve high biodegradation of organics (COD and BOD reductions typically 60–99% depending on system) and are essential for breaking down biodegradable components; however, they may struggle with non-biodegradable fractions and require longer treatment times. Advanced oxidation processes (Fenton, ozonation) are very useful for degrading surfactants and other recalcitrant organics (removing ~65–75% of COD and surfactants in studies), and they serve well as polishing steps. Novel methods like hydrodynamic cavitation show promise especially against certain contaminants (e.g., 70%+ surfactant removal), but on their own are insufficient for complete treatment. Crucially, hybrid systems combining these methods consistently demonstrated the highest performance often exceeding 95% removal for multiple parameters and producing effluents that meet or approach reuse standards. Integrated approaches are thus regarded as the optimal solution for treating CWW to a level safe for discharge or recycling.

Technology Trends: There is a clear movement toward integration of processes and reuse-oriented treatment. Many studies focused not just on pollutant removal, but on enabling water recycling on-site at car washes (closing the loop). Membrane and disinfection steps have been added to ensure reclaimed water is free of pathogens and meets clarity standards for reuse. Another trend is the exploration of eco-friendly materials e.g., natural coagulants (Moringa, humic substances) and bio-adsorbents (agricultural waste like bagasse, sawdust) to reduce chemical usage and cost. EC has gained prominence as a versatile core treatment; multiple papers emphasized its strengths and looked at optimizing it within hybrids. Research interest in EC is high because it often delivers broad-spectrum removal with simple equipment, and improvements in energy efficiency could make it even more attractive.

Gaps and Future Work: Despite significant progress, several research gaps remain. One key area is optimization and scale-up of electrocoagulation systems: further studies are needed to minimize energy consumption and electrode costs (e.g., through better power management, hybrid electrode materials, or recovering by-products from EC sludge). Long-term pilot trials of EC-based hybrid systems would help evaluate operational stability, maintenance needs, and overall economics (including sludge handling) under real-world conditions. Integrated system design also warrants more investigation – determining the optimal sequencing of processes (for example, the best way to pair EC with bio or with membranes, etc.), as well as compact configurations suitable for small commercial installations. The impact of variability in car wash effluent (due to different cleaning chemicals or seasonal effects) on treatment efficiency is another area for ongoing research, to ensure systems are robust. Lastly, life-cycle assessments and cost-benefit analyses will be important to convince industry to adopt advanced systems; demonstrating water savings, regulatory compliance benefits, and potential recovery of resources (like reusing sludge or capturing energy) could support wider implementation.

In summary, treating CWW effectively requires a tailored, often multi-stage approach reflecting the wastewater's complex makeup. Single-step solutions seldom meet all discharge or reuse criteria, but when processes are combined particularly with electrocoagulation as a central component the results consistently show superior contaminant removal, enhanced reliability, and sustainable water reuse potential. Going forward, continued improvements in EC technology and smart integration of treatment methods will pave the way for more efficient, energy-conscious, and affordable systems, helping car wash facilities align with environmental goals and water conservation targets (e.g., the UN SDG 6 for clean water and sanitation).

Table 1: Summary of Car Wash Wastewater Treatment Technologies (2015–2025 Studies)

Treatment Method	Typical Removal Performance (example results)	Key Benefits	Limitations
Biological (MBR, MBBR)	COD reduction up to 99% in advanced MBR (with BOD, surfactants ≥97% removed); simpler biofilm systems ~60–70% COD removal; Turbidity up to 90–94% removed.	- Degrades biodegradable organics thoroughly - Can significantly reduce BOD/COD and surfactants - MBR produces disinfected, reuse-quality effluent	- Ineffective for non-biodegradable pollutants - Requires long retention time & stable conditions - Fouling issues in MBR membranes, higher operational complexity
Membrane Filtration (UF/NF/RO)	Suspended solids & turbidity removal >95%; NF can achieve ~98% COD and 100% phosphate removal; MF alone gives ~40–80% COD removal; complete bacteria removal with UF/NF.	- Produces high-quality effluent (suitable for recycle) - Effective removal of fine particles and microbes - Modular and space-efficient	- Prone to fouling by oils/solids, needs pretreatment - High pressure/energy demand for NF/RO - Membrane replacement and concentrate disposal required
Adsorption	Excellent O&G removal (up to 100% in kapok fiber tests); COD removal ~90%+ with optimized activated carbon or composite media; Heavy metal reductions 60–85% reported.	- Simple operation, no high energy input - Low-cost natural adsorbents can be used - Targets specific pollutants (e.g., oils, dyes) effectively	- Adsorbents saturate and need regeneration/replacement - Not comprehensive for all pollutants if used alone - Generates spent media (solid waste)
Electrocoagulation (EC)	Turbidity and TSS removal typically 95–99%; COD removal commonly 80–97%; Surfactants and O&G largely removed (often >90%); e.g. 97.5% COD, 98.5% turbidity achieved with Al electrodes.	- High effectiveness for a broad range of contaminants in one step - Requires only electricity (no external chemical dosing) - Easy to combine with other processes (acts as pretreatment or polishing)	- Energy consumption can be significant if not optimized - Electrodes corrode and must be replaced periodically - Produces sludge that needs handling
Advanced Oxidation (Fenton, Ozone)	Capable of 60–75% COD removal and ~70–80% surfactant degradation; Ozone-based systems achieved ~96% COD when combined with filtration; Provides	- Breaks down recalcitrant organics that resist other treatments - Improves biodegradability of effluent - Can achieve high	- Requires chemicals (H_2O_2) or reactive gases (O_3) and energy - Optimal at low pH (Fenton) – may need pH adjustment - Risk of forming by-

	disinfection (ozone/UV kill bacteria).	disinfection and decolorization	products, needs controlled operation
Hydrodynamic Cavitation	Anionic surfactants removal up to ~77%; Non-ionic surfactants ~35%; COD reduction modest (~20–30%); Some microbial inactivation due to extreme conditions.	- No chemical additives needed (uses fluid dynamics) - Effective for breaking down certain surfactants - Can be combined with other AOPs for greater effect	- Limited COD removal as a standalone - Energy required to maintain cavitation (pumps) - Potential erosion of equipment, emerging technology
Hybrid/Integrated Systems	Typically >90–95% COD, turbidity, O&G removal achievable; e.g., combined systems report 96–99% COD and turbidity reduction; multi-stage processes meet reuse standards (zero detectable E. coli, etc.).	- Synergistic pollutant removal (each stage complements others) - Highest likelihood of meeting strict discharge/reuse criteria - Flexible design can be tailored to wastewater characteristics	

REFERENCES

1. Al-Gheethi, A. A., Mohamed, R. M. S. R., Rahman, M. A. A., Johari, M. R., & Kassim, A. H. M. (2016). Treatment of Wastewater from Car Washes Using Natural Coagulation and Filtration System. IOP Conference Series: Materials Science and Engineering, 136(1). https://doi.org/10.1088/1757-899X/136/1/012046
2. Davarnejad, R., Sarvmeili, K., & Sabzehei, M. (2019). Car wash wastewater treatment using an advanced oxidation process: A rapid technique for the COD reduction of water pollutant sources. Journal of the Mexican Chemical Society, 63(4), 164–175. https://doi.org/10.29356/jmcs.v63i4.786
3. El-Ashtoukhy, E.-S. Z., Amin, N. K., & Fouad, Y. O. (2015). Treatment of real wastewater produced from Mobil car wash station using electrocoagulation technique. Environmental Monitoring and Assessment, 187(10). https://doi.org/10.1007/s10661-015-4836-4
4. Emamjomeh, M. M., Jamali, H. A., Naghdali, Z., & Mousazadeh, M. (2019). Carwash wastewater treatment by the application of an environmentally friendly hybrid system: An experimental design approach. Desalination and Water Treatment, 160, 171–177. https://doi.org/10.5004/dwt.2019.24382
5. Etchepare, R., Zaneti, R., Azevedo, A., & Rubio, J. (2015). Application of flocculation–flotation followed by ozonation in vehicle wash wastewater treatment/disinfection and water reclamation. Desalination and Water Treatment, 56(7), 1728–1736. https://doi.org/10.1080/19443994.2014.951971
6. Fayed, M., Shewitah, M. A., Dupont, R. R., Fayed, M., & Badr, M. M. (2023). Treatability Study of Car Wash Wastewater Using Upgraded Physical Technique with Sustainable Flocculant. Sustainability (Switzerland), 15(11). https://doi.org/10.3390/su15118581
7. Han, J., Luo, H., & Wang, B. (2018). Experimental study on car washing wastewater treatment by coagulation and nano filtration method. Desalination and Water Treatment, 125, 285–289. https://doi.org/10.5004/dwt.2018.22829
8. Hoseinzadeh, E., Gholi-fam, A., & Faramarzi, M. (2024). Treatment of real carwash wastewater using high-efficiency and energy-saving electrocoagulation technique. Sustainable Chemistry and Pharmacy, 41. https://doi.org/10.1016/j.scp.2024.101688
9. Hu, C.-Y., Kuan, W.-H., Ke, L.-W., & Wu, J.-M. (2022). A Study of Car Wash Wastewater Treatment by Cyclo-Flow Filtration. Water (Switzerland), 14(9). https://doi.org/10.3390/w14091476

10. Ibrahim, M. S. S., & Hashim, N. H. (2018). Removal of oil and grease and anionic surfactants in synthetic car wash wastewater using kapok fiber: A batch-scale study | Penyingkiran minyak dan gris dan anionik surfaktan dalam air sisa sintetik basuhan kereta menggunakan fiber kapok: kajian skala-kel. Malaysian Journal of Analytical Sciences, 22(4), 735–741. https://doi.org/10.17576/mjas-2018-2204-20
11. Latha, A., Ganesan, R., Venkatesan, G., & Krishnakumari, B. (2023). Comparison studies on treatment of automobile wash wastewater by filtration techniques using alum sugarcane bagasse and wood dust. Desalination and Water Treatment, 316, 160–167. https://doi.org/10.5004/dwt.2023.30183
12. Lebiocka, M., Montusiewicz, A., Grządka, E., Pasieczna-Patkowska, S., Montusiewicz, J., & Szaja, A. (2024). Hydrodynamic Cavitation as a Method of Removing Surfactants from Real Carwash Wastewater. Molecules, 29(20). https://doi.org/10.3390/molecules29204791
13. Maqbool, F., Kamal, R., Bhatti, Z. A., Pervez, S., Sajid, M., Haleem, K., & Faridullah. (2019). Effects of hydrocarbon degrading inoculum for carwash effluent treatmenin a uasb reactor. Desalination and Water Treatment, 164, 31–38. https://doi.org/10.5004/dwt.2019.24396
14. Medel, A., Ramírez, J. A., Cárdenas, J., Sirés, I., & Meas, Y. (2019). Evaluating the electrochemical and photoelectrochemical production of hydroxyl radical during electrocoagulation process. Separation and Purification Technology, 208, 59–67. https://doi.org/10.1016/j.seppur.2018.05.021
15. Moazzem, S., Ravishankar, H., Fan, L., Roddick, F., & Jegatheesan, V. (2020). Application of enhanced membrane bioreactor (eMBR) for the reuse of carwash wastewater. Journal of Environmental Management, 254. https://doi.org/10.1016/j.jenvman.2019.109780
16. Moazzem, S., Wills, J., Fan, L., Roddick, F., & Jegatheesan, V. (2018). Performance of ceramic ultrafiltration and reverse osmosis membranes in treating car wash wastewater for reuse. Environmental Science and Pollution Research, 25(9), 8654–8668. https://doi.org/10.1007/s11356-017-1121-9
17. Mohammadi, M. J., Salari, J., Takdastan, A., Farhadi, M., Javanmardi, P., Yari, A. R., Dobaradaran, S., Almasi, H., & Rahimi, S. (2017). Removal of turbidity and organic matter from car wash wastewater by electrocoagulation process. Desalination and Water Treatment, 68, 122–128. https://doi.org/10.5004/dwt.2017.20319
18. Rodriguez Boluarte, I. A., Andersen, M., Pramanik, B. K., Chang, C.-Y., Bagshaw, S., Farago, L., Jegatheesan, V., & Shu, L. (2016). Reuse of car wash wastewater by chemical coagulation and membrane bioreactor treatment processes. International Biodeterioration and Biodegradation, 113, 44–48. https://doi.org/10.1016/j.ibiod.2016.01.017
19. Rosli, M. A., Sa'ari, S. N., Rahman, M. A. A., Rahman, M. F. A., Sunar, N. M., Awang, M., & Najib, M. Z. M. (2020). The effectiveness of macrocomposite adsorbent for treatment of COD and suspended solid of car wash water effluent. International Journal of Emerging Trends in Engineering Research, 8(1 Special), 34–39. https://doi.org/10.30534/ijeter/2020/0681.22020
20. Saad, F. N. M., Quan, O. C., Izhar, T. N. T., Hwidi, R. S. A., & Syafiuddin, A. (2024). Evaluation of the use of activated carbon derived from coconut shells to treat car wash wastewaters. Desalination and Water Treatment, 319. https://doi.org/10.1016/j.dwt.2024.100452
21. Uçar, D. (2018). Membrane processes for the reuse of car washing wastewater. Journal of Water Reuse and Desalination, 8(2), 169–175. https://doi.org/10.2166/wrd.2017.036
22. Włodyka-Bergier, A., Mazur, R., Kowalewski, Z., & Bergier, T. (2023). Research on the possibility of using moving bed biofilm reactors for treating car wash wastewater. Desalination and Water Treatment, 301, 150–158. https://doi.org/10.5004/dwt.2023.29777