

Optimizing Energy and Water Efficiency in Automated Car-Wash Facilities in Saudi Arabia: A Sustainable Operations Framework

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Abstract- Automated car-wash facilities combine intensive water use with pumping, pressurization, air movement, heating, treatment, and control loads, creating a coupled water-energy problem that is especially consequential in Saudi Arabia. This review synthesizes recent evidence on car-wash wastewater treatment, water reuse, energy optimization, digital monitoring, Saudi water-resource conditions, and the Kingdom's evolving regulatory context. It also adds a transparent sector-scale estimate: a commercial business directory listed approximately 2,656 car-wash locations in Saudi Arabia in April 2026, while an earlier market assessment reported about 14 million professional washes in 2022. Applying published water-use intensities gives an indicative national commercial-wash demand of roughly 0.84-2.63 million m³ (approximately the same number of metric tonnes) of water per year at the 2022 wash volume; this is a scenario estimate rather than an official national inventory. The proposed framework integrates demand prevention, segregated collection, fit-for-purpose reclamation, hardness and scale control, energy-aware equipment operation, digital supervision, and performance governance. It responds directly to the transition away from manual washing at fuel stations, where Saudi requirements permit only automatic car-wash systems. The recommended operating package targets 70-80% water recovery where technically feasible, reserves softened or RO-quality water for scale-sensitive and final-rinse duties, and uses lower-grade reclaimed water for prewash, underbody and compatible brush stages. The framework provides concrete design, retrofit and monitoring actions to reduce freshwater use while protecting pumps, nozzles, heat exchangers, membranes and piping from fouling and limescale.

Keywords: automated car wash; water reuse; energy efficiency; Saudi Arabia; water-energy nexus; wastewater treatment; IoT; sustainable operations

I. INTRODUCTION

Automated vehicle washing is a service operation in which resource efficiency depends on the interaction of mechanical cleaning, water delivery, wastewater separation, treatment,

reuse, and equipment control. Car-wash wastewater typically contains suspended solids, road dust, oils, grease, surfactants, and variable dissolved constituents; its composition changes with washing chemistry, vehicle condition, local dust, and process configuration (Dadebo et al., 2022; Kazembeigi et al., 2023). These characteristics make recycling technically attractive but operationally nontrivial. Reclaimed water must be sufficiently clean for the intended wash stage, yet producing unnecessarily high-quality water can impose avoidable pumping, aeration, chemical, and membrane energy. The central sustainability problem is therefore not simply how to treat car-wash wastewater, but how to coordinate water quality, quantity, energy, equipment reliability, and customer-facing wash performance.

Saudi Arabia provides a particularly important context for this problem. The Kingdom's arid climate, limited renewable freshwater, expanding urban demand, and reliance on energy-intensive water supply make water conservation and reuse strategically important (Dawoud et al., 2022; Alhajri et al., 2025). Water and energy should consequently be assessed as a nexus rather than as independent utility inputs. Alresheedi et al. (2022) show that water-supply choices in arid regions have direct energy and carbon consequences, while Almulhim and Al-Saidi (2023) argue that Saudi circular-economy progress requires more explicit integration across water, energy, and resource systems. For a car wash, every liter avoided, recycled, pumped, filtered, or discharged changes both the water balance and the facility's electricity requirement.

The scale of the activity also justifies treating vehicle washing as a national water-efficiency opportunity. A commercial location database listed approximately 2,656 car-wash businesses in Saudi Arabia as of 1 April 2026; because this is a directory count rather than a government licensing register, it should be interpreted as an indicative active-site estimate rather than an official total. A market assessment for 2022 reported approximately 14 million professional car washes nationally, of which manual washing represented the majority

at that time. Published studies report approximately 60-70 L per vehicle for some professional systems, while monitored saloon-car washing has ranged around 139 L for semi-automated and 188 L for manual facilities. Applying 60-188 L per wash to the 14 million-wash benchmark gives an indicative annual demand of 0.84-2.63 million m³, equivalent to roughly 0.84-2.63 million metric tonnes of water. The range is intentionally broad because Saudi-specific, audited water-throughput data are not publicly available and wash type, vehicle size, dust load and recycling practice vary widely.

Recent car-wash research has substantially improved understanding of treatment technologies. Reviews identify coagulation, electrocoagulation, filtration, biological treatment, adsorption, advanced oxidation, and membrane systems as recurring options, with hybrid trains often required where reuse quality is demanding (Kuan et al., 2022; Torkashvand et al., 2021). Pilot and laboratory studies show that membranes can produce high-quality recycled water, but fouling, pretreatment requirements, concentrate handling, and hydraulic conditions govern practical performance (Moazzem et al., 2020; Tomczak and Gryta, 2023; Tomczak et al., 2025). Other approaches, including cyclo-flow filtration, enhanced physical separation, and hydrodynamic cavitation, illustrate the value of compact or targeted processes when specific contaminants dominate (Hu et al., 2022; Fayed et al., 2023; Lebiocka et al., 2024). These studies are technically informative, but they rarely treat the entire automated facility as an integrated operations system.

Regulation is also changing the operating model. The Saudi requirements for fuel stations and service centers specify that only automatic car washes are permitted inside fuel stations and that manual car washes are prohibited. The same requirements call for treatment of used water through approved methods, oil/grease control and allow recycling for industrial uses within the station. April 2026 reporting, citing the Permanent Executive Committee for Fuel Stations and Service Centers at the Ministry of Energy, stated that existing manual operations at fuel stations and service centers may continue only until their current licences expire, after which automated systems are required; the reporting also described municipalities as actively licensing and enforcing the transition (Fareed, 2026). The practical effect is a shift from labour-intensive washing toward equipment-intensive operations: throughput and process repeatability can improve, but water quality, pretreatment, scaling, sensor reliability, preventive maintenance and recycling performance become more critical to business continuity.

A second body of literature offers transferable lessons on energy-aware water management. Wastewater facilities can reduce energy demand through benchmarking, process optimization, flexible scheduling, and integrated control (Nakkasunchi et al., 2021; Bolorinos et al., 2023). Water-reuse studies also demonstrate that treatment configuration and conveyance materially influence lifecycle energy intensity (Tow et al., 2021; Santos et al., 2021). Digital monitoring can improve control by linking sensors, Internet-of-Things architectures, and machine-learning models to water quality and equipment behavior, although data quality, model transparency, and reproducibility remain limitations (Jan et al., 2021; Lowe et al., 2022; Abunama et al., 2024). Automated car washes are smaller than municipal treatment plants, but their repetitive cycles, discrete operating states, and measurable utility flows make them suitable for similar optimization principles.

The literature therefore presents a fragmentation problem. Car-wash studies concentrate mainly on pollutant removal and reuse feasibility; energy studies concentrate on larger treatment systems; digital studies address monitoring and modeling; and Saudi studies address national water scarcity, reuse, and circularity. What is missing is an integrated framework translating these streams into operational rules for automated car-wash facilities in Saudi Arabia. This review addresses that gap by synthesizing the evidence around joint water-energy efficiency, explicitly considering the trade-off between greater water recovery and the resource burden required to achieve it.

II. AIM OF THE STUDY

The aim is to develop an evidence-based sustainable operations framework for optimizing water and energy efficiency in automated car-wash facilities in Saudi Arabia. Rather than selecting a single treatment technology, the review evaluates how demand reduction, staged water reuse, treatment intensity, equipment energy use, digital control, and governance can be coordinated so freshwater savings do not create disproportionate electricity, chemical, maintenance, or waste burdens.

III. RESEARCH OBJECTIVES

Five objectives guide the review. First, to synthesize recent evidence on water demand, wastewater characteristics, and reuse technologies relevant to automated car washing. Second, to identify the principal energy loads and operational

levers associated with water delivery and on-site reclamation. Third, to assess how sensors, IoT systems, machine learning, and supervisory control can support adaptive operation. Fourth, to interpret these findings for Saudi Arabia's arid, water-energy constrained context. Fifth, to formulate measurable operating principles and performance indicators for a facility-level sustainable operations framework.

IV. RESEARCH QUESTIONS

The review addresses five questions. What combinations of demand prevention, collection, treatment, and reuse can reduce freshwater intensity without compromising wash performance? Which water-recovery decisions create the largest energy and maintenance trade-offs? How can automated control adjust flow, pressure, treatment, and reuse to changing vehicle and wastewater conditions? Which Saudi water-security, circular-economy, and acceptance factors should shape implementation? Finally, which indicators can managers use to compare facilities and continuously improve water-energy performance rather than optimizing isolated equipment items?

V. REVIEW METHODOLOGY

A structured integrative review was used because the research question spans several evidence domains that a single technology-focused meta-analysis cannot adequately capture. The methodological logic follows the clear search, classification, and synthesis sequence used in the attached structural reference, while avoiding its bibliometric design and its historical screening counts. The attached paper demonstrates the value of separating search strategy, data classification, analysis, technology comparison, sustainability interpretation, and future perspectives; this review adopts that organizational discipline but builds an independent evidence base and focuses on Saudi operations (Dadebo et al., 2022).

Searches focused on four evidence clusters: car-wash water use and wastewater treatment; energy efficiency and the water-energy nexus; smart monitoring and data-driven control; and Saudi water reuse, scarcity, and circular-resource management. The principal discovery databases were Scopus and Web of Science Core Collection, supplemented by ScienceDirect, SpringerLink, Wiley Online Library, and publisher platforms for full bibliographic verification. Google Scholar was used only for supplementary citation chaining where a peer-reviewed source was already identified. Crossref metadata and publisher landing pages were used to verify DOI

strings and bibliographic details before inclusion. Peer-reviewed literature remained the basis for technical treatment and efficiency conclusions. For the revised Saudi context, official government requirements were additionally used to describe fuel-station car-wash rules, and current commercial/market datasets were used only to provide clearly labelled indicative counts and national-scale water-demand scenarios; these non-peer-reviewed sources were not used to infer treatment efficacy.

The primary publication window was 2020-2025, reflecting the user's requirement for recent evidence. Search concepts included combinations of "car wash", "carwash", "vehicle washing", "wastewater", "water reuse", "recycling", "automated", "energy efficiency", "specific energy consumption", "water-energy nexus", "Saudi Arabia", "arid", "IoT", "smart monitoring", "machine learning", "process control", "membrane", "electrocoagulation", and "circular economy". We adapted Boolean combinations to database syntax. Earlier references were not needed for the final evidence set because the six-year window included sufficiently relevant peer-reviewed work.

Inclusion required peer-reviewed English-language journal articles that directly contributed to at least one framework element: car-wash wastewater characterization or treatment; water-reuse energy; wastewater energy optimization; digital water monitoring or automation; or Saudi water-reuse and resource-nexus conditions. Studies outside car washing were retained only when their operational principle was transferable, such as pump-energy optimization, sensor-based water-quality monitoring, treatment-energy modeling, or flexible energy management. We excluded conference papers, theses, non-peer-reviewed reports, duplicate records, unverifiable bibliographic items, and studies lacking a credible connection to the framework. The evidence set was deliberately bounded to 30 verified journal references rather than expanded with weakly relevant sources.

Screening proceeded qualitatively from title and abstract relevance to full-text or detailed publisher-record assessment. No retrospective identification, exclusion, or full-text counts are reported because this review was not prospectively registered and those numbers were not captured under an auditable systematic-review protocol; inventing them would create false precision. Quality appraisal considered five dimensions: clarity of study design, transparency of operating conditions, use of real or representative wastewater, completeness of water-quality or energy outcomes, and

transferability to facility operation. Evidence was treated as stronger when it reported real wastewater, pilot or field conditions, explicit operational parameters, and multiple performance outcomes rather than a single removal percentage.

Data were coded into a thematic matrix covering freshwater reduction, recycle configuration, contaminant control, treatment energy, pump and blower loads, fouling and maintenance, digital sensing, algorithmic control, Saudi applicability, and implementation risks. Synthesis was

interpretive rather than statistical because designs, influent characteristics, treatment trains, units, and reporting conventions were heterogeneous. The review therefore compares mechanisms and trade-offs rather than pooling incompatible efficiencies. Figure 1 summarizes the methodology. Table 1 then converts the resulting evidence into intervention domains. Methodological limitations include publication bias toward successful treatment trials, sparse energy measurements in car-wash studies, limited Saudi-specific facility data, and the use of municipal wastewater literature for carefully bounded operational transfer.

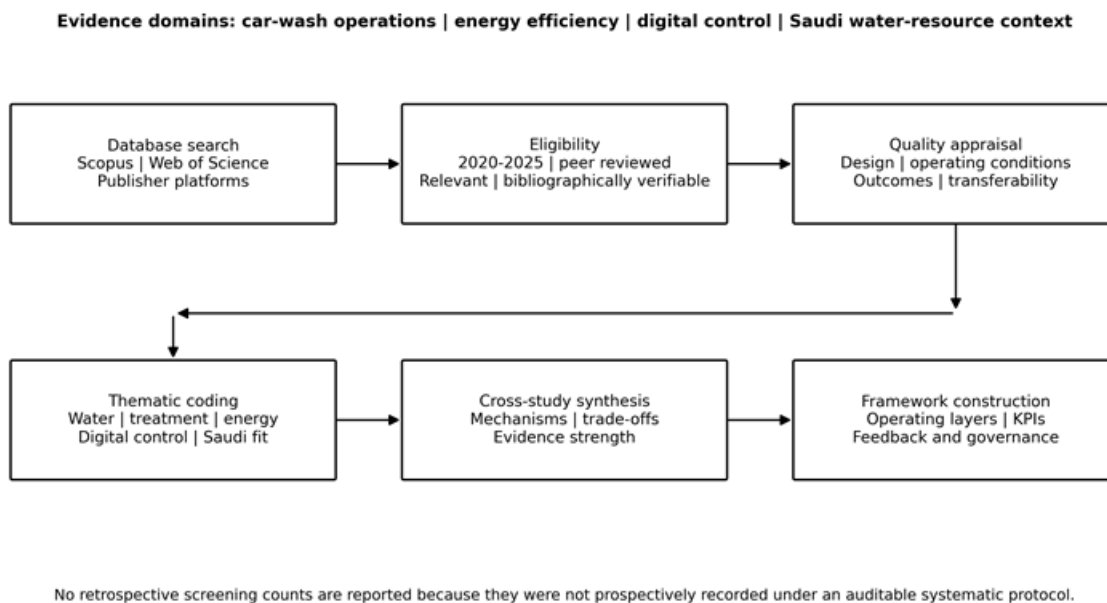


Figure 1. Structured integrative-review workflow used to build the sustainable operations framework. Screening counts are intentionally omitted because they were not prospectively recorded under an auditable systematic-review protocol.

Table 1. Evidence synthesis across sustainable car-wash intervention domains.

Intervention domain	Operational mechanism	Water implication	Energy / reliability implication	Representative evidence
Demand prevention	Recipe control, leak detection, optimized nozzle flow and pressure	Reduces freshwater and wastewater generation before treatment	Avoids pumping and treatment of unnecessary volume; must preserve wash quality	Dadebo et al. (2022); Kazembeigi et al. (2023)
Front-end separation	Grit, solids and free-oil removal before polishing	Improves recoverable-water quality and protects downstream units	Generally lowers fouling and high-pressure treatment burden	Hu et al. (2022); Fayed et al. (2023)
Fit-for-purpose reuse	Cascade reclaimed water to prewash/underbody; reserve higher quality for sensitive rinse	Raises effective reuse without polishing every litre to the same standard	Can reduce membrane duty and cleaning compared with uniform high-grade treatment	Kuan et al. (2022); Torkashvand et al. (2021)
Advanced polishing	Membrane, electrochemical or targeted oxidation/cavitation where quality requires it	Enables higher-quality reuse and protects finish-sensitive stages	Pressure, fouling, electrodes, cleaning and reject create energy/maintenance trade-offs	Gönder et al. (2020); Tomczak et al. (2025); Lebiocka et al. (2024)
Energy-aware operation	Efficient pump duty, VFD control, buffered treatment, idle-load management	Indirectly supports stable recycle by matching production to demand	Reduces inefficient part-load operation and can create demand flexibility	Nakkasunchi et al. (2021); Bolorinos et al. (2023)
Digital supervision	Online flow, quality, pressure and power sensing with analytics	Detects leaks, poor quality and abnormal losses	Enables adaptive set-points and predictive maintenance; requires reliable data	Jan et al. (2021); Lowe et al. (2022); Abunama et al. (2024)

VI. THEMATIC LITERATURE REVIEW AND CRITICAL ANALYSIS

6.1 Saudi resource context and the need for joint optimization.

Saudi water management increasingly emphasizes reuse, diversification, and resource efficiency because aridity and energy-intensive production constrain conventional water provision (Dawoud et al., 2022; Alhajri et al., 2025). This context changes what “efficient” car washing means. A facility that lowers its direct freshwater meter through recycling but operates an unnecessarily energy-intensive treatment train may transfer rather than solve resource burdens. Alresheedi et al. (2022) similarly show that water systems in arid settings should be assessed together through water, energy, and carbon. Circular-economy

scholarship for Saudi Arabia reinforces the importance of closing resource loops while embedding them within wider sustainability policy (Almulhim and Al-Saidi, 2023). Ali et al. (2022) extend this logic to wastewater by framing treated water, energy, and recoverable materials as resources rather than disposal problems.

Public and institutional acceptance also matters. Mu'azu et al. (2020) found that acceptance of treated wastewater reuse in Saudi Arabia varies by intended use and perception, while Alzahrani et al. (2023) show that trust in responsible authorities can support acceptance in another reuse context. For automated car washes, reuse occurs within a controlled, non-potable industrial service, but operators still need visible hygiene, odor control, clarity, and equipment-

protection standards. Aljeddani (2023) and Alnaser et al. (2023) highlight broader Saudi interest in fit-for-purpose reuse and context-sensitive treatment. This suggests that a sustainable car-wash framework should combine quantitative efficiency with transparent quality assurance.

6.1.2 Water hardness, limescale and automatic-equipment reliability.

Automatic conversion does not by itself guarantee sustainable performance. Feed-water hardness and dissolved solids must be treated as reliability variables because calcium- and magnesium-rich water can deposit scale in small-bore piping, spray nozzles, valves, heaters, pumps and membrane systems. Saudi water quality is spatially variable because desalinated water is blended with groundwater and surface sources. National monitoring reported a suggested hardness range of about 60-80 mg/L as CaCO₃ for supplied water, while groundwater and dam sources can be much harder; other Saudi groundwater studies have reported hard to very hard conditions. In a car wash, scale narrows flow passages, alters nozzle spray patterns, increases pump differential pressure and energy demand, interferes with level/quality sensors and raises chemical cleaning and replacement frequency. A practical design rule is therefore to test source water for total hardness, alkalinity, conductivity/TDS and silica during commissioning and seasonally thereafter. Where total hardness is persistently above about 150 mg/L as CaCO₃, softening should be evaluated for scale-sensitive equipment; where spot-free finish is required, RO or deionized water should be reserved for the final rinse rather than applied to the complete wash volume. These thresholds are operational screening values, not Saudi regulatory limits.

6.1.1 Fuel-station regulation and the transition from hand wash to automatic systems. Saudi fuel-station/service-center requirements materially affect the sector's technology pathway. The applicable requirements permit only automatic car-wash systems inside fuel stations and prohibit manual car washing in those locations. They also require appropriate drainage and treatment, including oil/grease separation, and support reuse of treated water for industrial purposes within the station (Permanent Executive Committee for Service Centers and Fuel Stations, 2023).

Contemporary reporting in April 2026, quoting the Permanent Executive Committee for Fuel Stations and Service Centers at the Ministry of Energy, stated that existing manual washes at fuel stations and service centers could continue only until expiry of their current licences, after which automated systems would be required; it also reported that Saudi municipalities had begun actively licensing and enforcing the transition (Fareed, 2026). The expected effects are higher capital expenditure for gantry/tunnel equipment and reclaim systems; reduced dependence on manual labour; shorter and more repeatable wash cycles; a stronger need for technician skills and preventive maintenance; and a larger operational penalty if poor-quality water causes scale, fouling or nozzle blockage. The regulation therefore creates a strong case for coupling automation with water recycling and water-conditioning specifications rather than treating the automatic machine as a stand-alone investment.

6.2 Preventing demand before treating wastewater.

The first operational priority is to avoid generating unnecessary wastewater. Automated systems offer an advantage over manual washing because they can standardize nozzle sequencing, dwell time, detergent dosing, pressure, conveyor speed, and vehicle-class recipes. The literature consistently shows that car-wash water quantity and quality vary substantially with wash configuration and incoming contamination (Dadebo et al., 2022; Kazembeigi et al., 2023). Consequently, fixed high-flow recipes are unlikely to be optimal across sedans, SUVs, lightly soiled vehicles, and vehicles carrying heavy dust loads. Demand prevention should begin with metering each wash zone, detecting stuck valves and leaks, selecting nozzles that maintain cleaning force at lower flow, and using pressure only where it contributes to soil removal.

This prevention logic is important because every liter not applied avoids multiple downstream burdens: pumping, collection, treatment, disinfection, storage, and possibly reject disposal. It also protects recycling equipment from hydraulic peaks. Water reduction, however, cannot be pursued blindly. Excessively low rinse flow can leave surfactant residues or reduce customer satisfaction, while aggressive air substitution may increase blower electricity. Sustainable optimization therefore requires a marginal

perspective: the relevant question is whether the next unit of water or energy materially improves the wash result. A useful operating hierarchy is “avoid, cascade, treat, polish”, placing high-grade treatment after process redesign rather than before it.

6.3 Segregated collection and fit-for-purpose reuse.

Treatment literature strongly supports recycling, but it also demonstrates that different contaminants require different barriers. Kuan et al. (2022) describe a broad family of on-site physical, chemical, biological, and membrane approaches. Fayed et al. (2023) show that physical separation combined with coagulation can substantially improve car-wash effluent quality, while Hu et al. (2022) demonstrate compact cyclo-flow filtration for reducing suspended solids and organic load. These findings favor front-end removal of grit, settleable solids, and free oil before high-energy polishing.

Water should then be cascaded by quality rather than mixed indiscriminately. Relatively lower-quality reclaimed water can serve underbody, wheel, and early prewash stages, while the final spot-sensitive rinse may require higher-quality water. This strategy reduces the volume subjected to advanced treatment. Membrane systems can support high-quality reuse: Moazzem et al. (2020) reported high-quality recyclable water from an enhanced membrane bioreactor, and Tomczak and Gryta (2023) demonstrated ultrafiltration behavior for car-wash wastewater. Pilot-scale work by Tomczak et al. (2025) reinforces the relevance of membrane fouling and feed composition at larger operating scales. Torkashvand et al. (2021) similarly identify flux decline and permeate changes as central membrane limitations.

A critical implication is that maximum contaminant rejection does not automatically translate into sustainable operation. Membrane pressure, cross-flow, cleaning frequency, pretreatment, and reject volume all carry water, energy, and maintenance costs. Electrocoagulation followed by nanofiltration can achieve effective reuse, but Gönder et al. (2020) show that operating variables such as temperature, stirring, and electrode configuration affect both removal and energy performance. Lebiocka et al. (2024) explicitly combine contaminant removal with energy input in selecting hydrodynamic-cavitation conditions,

demonstrating the value of multi-criteria rather than single-metric optimization. The preferable treatment train is therefore the least resource-intensive combination that repeatedly meets the quality requirement of the intended reuse stage.

For Saudi automatic facilities, the preferred recycling architecture is a staged loop rather than one high-grade treatment train for all uses. Stage 1 should use trench screens, grit/sediment settlement and an oil-water separator; Stage 2 should apply multimedia or sand filtration, with activated carbon or equivalent polishing where surfactant/odor carryover requires it; Stage 3 should use disinfection and, only for the fraction that needs high quality, ultrafiltration and/or RO/DI. Reclaimed water should first be assigned to underbody, wheel, pre-soak and early wash stages, while softened or low-TDS water is retained for scale-sensitive chemical mixing and the final spot-free rinse. WaterSense guidance similarly identifies reclamation as the largest vehicle-wash saving opportunity and recommends at minimum separating grit, oil and grease before reuse, with additional filtration, oxidation, membranes or deionization as the reuse point becomes more quality-sensitive. This fit-for-purpose cascade reduces membrane throughput, RO reject and chemical cleaning while keeping fresh water where it adds most value.

A practical freshwater-reduction target for a well-operated retrofit is to recover approximately 70-80% of applied wash water and drive freshwater demand toward 40-60 L per passenger vehicle, provided local water quality and wash-performance verification support the target. Published full-scale reclamation evidence has demonstrated nearly 70% recovery with less than 40 L of fresh water per wash. Sites should not chase 100% recycling because evaporation, vehicle carry-out, sludge dewatering, filter backwash and dissolved-solids accumulation require controlled make-up and blowdown. The operating objective is therefore the lowest stable freshwater make-up that does not cause salt build-up, odor, corrosion, scale, spotting or microbiological deterioration.

6.4 Energy drivers inside the automated facility.

Dominant electrical loads vary by equipment package, but pumping, high-pressure spray, air blowers, water heating (where used), treatment pumps, aeration, and

membrane pressure are common contributors. Energy optimization literature from wastewater systems provides relevant operational lessons even though plant scale differs. Nakkasunchi et al. (2021) show that energy benchmarking and optimization tools are fragmented when energy, resource recovery, and renewables are considered separately. For car washes, the analogous mistake is to optimize the reclaim unit while ignoring wash-bay pumps and dryers.

Variable-frequency drives and pressure-based control can reduce throttling losses where pump systems operate across variable demand. Storage can decouple treatment production from instantaneous wash cycles, allowing pumps and treatment units to operate closer to efficient duty points rather than repeatedly starting or running at inefficient partial loads. Bolorinos et al. (2023) demonstrate at wastewater facilities that storage and coordinated control can create energy flexibility; the principle is transferable to small facilities when tanks provide hydraulic buffering. However, shifting operation should never compromise water quality through excessive residence time, loss of disinfectant residual, or uncontrolled biological growth.

Water reuse energy must also be compared against the energy embodied in alternative supply. Tow et al. (2021) demonstrate that treatment configuration, conveyance, and process selection determine reuse energy, while Santos et al. (2021) show the value of comparing reuse against conventional supply through a water-energy nexus lens. In Saudi Arabia, desalination and water transport strengthen the strategic rationale for conservation, even though the marginal energy value at a given site depends on the utility system. Renewable energy can reduce grid impacts, but it does not justify wasteful treatment. Alqaed et al. (2021) and Bundschuh et al. (2021) show the broader technical potential of solar and renewable integration in water systems; for car washes, rooftop photovoltaic generation is best treated as a complement to efficiency, not a substitute.

6.5 Digital monitoring and adaptive control.

Automated car washes already operate through programmable sequences, making them suitable for resource-aware supervisory control. A minimum instrumentation layer should capture incoming

freshwater, reclaimed-water flow, selected tank levels, pump electricity, conductivity, turbidity or another validated solids proxy, pressure, and, where applicable, critical disinfection indicators. Jan et al. (2021) show how IoT architectures can move water-quality monitoring from intermittent manual testing toward real-time visibility, while also noting challenges involving power, communications, and system design. For harsh wash environments, sensor placement, fouling protection, calibration intervals, and data validation are therefore as important as connectivity.

Machine learning can add value after reliable measurement exists. Lowe et al. (2022) find that AI and machine-learning applications in water treatment can support prediction and optimization, but highlight recurring weaknesses in explainability, reproducibility, and data management. Alam et al. (2022) similarly show that AI can optimize treatment processes such as adsorption, while Abunama et al. (2024) synthesize growing evidence for machine-learning approaches to wastewater energy and emissions optimization. In a car wash, suitable applications include anomaly detection for leaks and filter blockage, predicting filter backwash needs, adaptive pump set-points, estimating reclaimed-water quality from multiple low-cost sensors, and predictive maintenance based on pressure and power signatures.

The control hierarchy should remain fail-safe. Machine-learning recommendations should operate within validated engineering limits, with deterministic overrides for low tank level, poor water quality, pump cavitation risk, excessive differential pressure, or disinfection failure. The framework therefore treats AI as an optimization layer, not as an autonomous replacement for process safeguards. Data should also be normalized by vehicle count and wash program so that managers can distinguish genuine efficiency improvement from changes in customer mix.

6.6 Integrated sustainable operations framework.

Figure 2 consolidates the evidence into six interacting layers. Layer one prevents avoidable demand through optimized wash recipes, leak control, and efficient nozzles. Layer two segregates flows so that relatively clean rinse water is not unnecessarily mixed with high-

solids streams. Layer three applies fit-for-purpose treatment, using low-energy solids and oil removal before more intensive polishing. Layer four optimizes electrical operation through efficient pump duty, variable speed, storage, maintenance, and appropriate renewable integration. Layer five uses sensors and supervisory analytics to adapt operation to actual conditions. Layer six governs performance through normalized indicators, quality assurance, maintenance records, and management review.

The critical feature is feedback. If turbidity rises, the response should not automatically be to increase every treatment stage; the system should first identify whether the cause is unusual vehicle soil, a failed separator, depleted filter media, poor chemical dosing, or hydraulic overload. Likewise, if energy per vehicle rises while water use remains stable, examine pump efficiency, membrane fouling, blower operation, and idle loads before altering wash quality. The framework converts sustainability from an equipment specification into a continuous operational discipline.

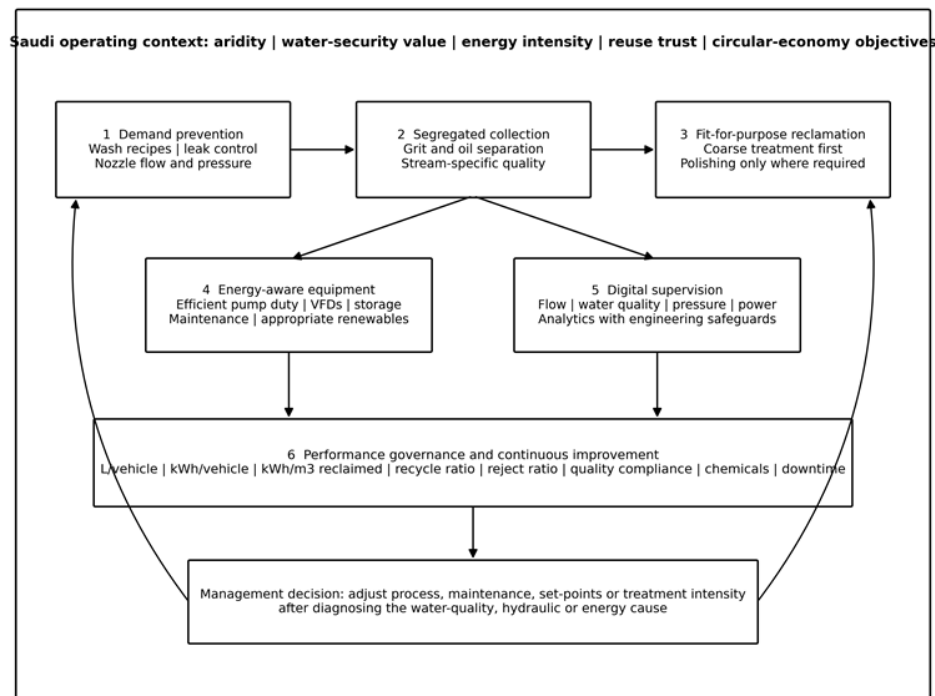


Figure 2. Sustainable operations framework for joint water-energy optimization in automated car-wash facilities in Saudi Arabia.

VII. DISCUSSION

The synthesis indicates that the most defensible optimization objective is not minimum freshwater use or minimum electricity use independently, but minimum combined resource burden subject to wash-quality, reclaimed-water-quality, reliability, and safety constraints. This distinction matters because many interventions move water and energy in opposite directions. Higher recycle ratios can decrease purchased water while increasing treatment pressure, cleaning frequency, and concentrate volume; lower

spray flow can reduce pumping and water but require longer cycle time; stronger air drying can reduce final rinse needs while increasing blower electricity. A sustainable facility therefore requires multi-objective decisions rather than technology rankings.

The evidence also supports a staged investment strategy. Basic metering, leak control, wash-recipe tuning, solids separation, and maintenance should precede advanced membranes or AI. These lower-complexity interventions improve the data and hydraulic stability needed for later treatment

optimization. When high-quality reuse is necessary, hybrid treatment may be justified, but its marginal benefit should be weighed against energy, consumables, and downtime. Gönder et al. (2020), Moazzem et al. (2020), and Tomczak et al. (2025) collectively show why membrane and electrochemical performance depends on operating context rather than nominal technology capability.

Saudi implementation adds four considerations. First, water savings have system value beyond the facility because avoided potable demand can reduce pressure on scarce resources and energy-intensive production. Second, the fuel-station rule that permits automatic rather than manual car washing creates a near-term retrofit market and should be used to embed reclaim systems at the design stage. Third, automation increases sensitivity to water quality: limescale and suspended solids can reduce nozzle performance, raise pumping energy and accelerate valve, heater, membrane and pipe maintenance. Fourth, reuse credibility depends on operator discipline and customer confidence. These factors mean that the business case should include avoided freshwater purchases and sewer/disposal volumes together with avoided scale-related downtime, nozzle replacement, membrane cleaning and rewash costs.

The proposed framework also changes how performance should be benchmarked. A facility with a high recycle ratio may perform poorly if electricity per vehicle, reject ratio, chemical use, or downtime are excessive. Conversely, a lower recycle ratio may be rational where polishing energy is disproportionately high or feed quality periodically deteriorates. Benchmarking should therefore use a dashboard of normalized indicators and preserve the causal link between operating decisions and outcomes.

A further operational principle concerns commissioning and verification. New or retrofitted facilities should be tested under several realistic wash programs rather than a single nominal duty point, because water pressure, vehicle throughput, reclaimed-water quality, and treatment energy interact dynamically. Commissioning should establish reference signatures for pump power, filter differential pressure, tank turnover, and water quality so later deviations can be diagnosed against a known efficient

condition. Periodic recommissioning is particularly valuable after nozzle replacement, chemical changes, membrane cleaning, control-software updates, or major seasonal shifts. Also evaluate performance over weekly and monthly periods rather than from isolated daily snapshots. Control charts can reveal gradual drift in water intensity, treatment energy, or pressure that individual alarms miss. Record weather, throughput, and vehicle mix as explanatory variables, and have multi-site operators benchmark comparable wash programs. This disciplined verification cycle helps distinguish equipment degradation from normal operating variation, prevents efficiency losses from becoming accepted as routine, and strengthens management reviews and future capital planning decisions.

VIII. RESEARCH GAPS AND FUTURE RESEARCH

The largest gap is the absence of Saudi field datasets that jointly report liters per vehicle, kilowatt-hours per vehicle, treatment energy per cubic meter, recycle ratio, reject volume, water-quality parameters, chemical use, and maintenance. Without these measurements, local design decisions rely heavily on international treatment evidence. Multi-season monitoring is particularly important because dust loading, heat, evaporation, and customer patterns can alter both wastewater strength and equipment performance.

Future studies should develop water-quality-energy response curves for complete automated facilities rather than isolated treatment units. Pilot research should compare cascaded reuse configurations, quantify when additional polishing yields diminishing resource returns, and incorporate membrane cleaning, electrode replacement, sludge, and downtime into lifecycle economics. Sensor fouling and calibration under car-wash aerosols also require targeted study. Digital research should prioritize explainable models trained on sufficiently diverse Saudi operating data, with prospective validation and clearly defined fail-safe boundaries. Finally, policy research should examine practical reuse-quality classes and benchmarking protocols for commercial vehicle washing so that regulation encourages measurable efficiency without prescribing a single technology.

IX. PRACTICAL, MANAGERIAL AND POLICY IMPLICATIONS

For facility managers, the recommended solution is a five-step Saudi Car-Wash Water and Reliability Package rather than a generic efficiency program. Step 1: meter incoming freshwater, reclaimed flow and total applied wash water and calculate L/vehicle by wash program for at least four weeks. Step 2: retrofit front-end separation (screen/grit trap + settlement + oil-water separator) and segregate relatively clean rinse returns from high-solids floor drainage. Step 3: establish a 70-80% recycle design objective where technically feasible, using reclaimed water for prewash, wheel, underbody and compatible brush stages and reserving fresh/conditioned water for chemical make-up and final rinse. Step 4: install hardness control: test hardness/TDS, soften hard feed where scaling risk is significant, and use RO/DI only for the final spot-free stream. Step 5: add differential-pressure, conductivity/TDS, turbidity and flow alarms tied to preventive maintenance. This package directly reduces freshwater demand while controlling the principal causes of automatic-equipment damage.

For designers and suppliers, the reclaim system should be specified as part of the automatic machine package, not as an optional downstream add-on. Tender documents should state the expected source-water hardness/TDS envelope; minimum separator and

filtration capacity; reclaim-tank turnover; automatic sludge purge; bypass and fail-safe logic; maximum allowable differential pressure across filters; water-quality set points for reuse stages; RO recovery and reject routing where RO is used; corrosion/scale-resistant materials; and access for cleaning nozzles, strainers and tanks. Suppliers should demonstrate water consumption per vehicle under at least three representative programs and state the freshwater fraction separately from total recirculated flow.

For regulators and utilities, implementation should connect the automatic-wash requirement at fuel stations to measurable water outcomes. A practical compliance model is to require a documented water balance, functional oil/grit separation, a defined reclaimed-water loop, periodic water-quality testing and monthly reporting of freshwater L/vehicle and recycle ratio. New automatic facilities should be commissioned against a declared freshwater-intensity target; existing fuel-station hand washes converting to automatic operation should be required to submit a conversion plan that includes water recycling and water-conditioning provisions. The key regulatory risk is otherwise a technology substitution in which manual washing disappears but poorly designed automatic equipment still consumes excessive fresh water or suffers high downtime from scaling. Performance-based verification would ensure that automation delivers the intended water-efficiency benefit.

Table 3. Pinpointed operational solutions for reducing freshwater use and protecting automatic car-wash equipment in Saudi Arabia.

Problem	Pinpointed intervention	Operational target / check
High freshwater consumption	Segregate drains; reclaim prewash/underbody/brush water; use fresh water only where quality requires it	Aim for 70-80% recycle where feasible; track fresh L/vehicle weekly
Limescale / hard-water damage	Test hardness, alkalinity and TDS; soften scale-sensitive feed; keep RO/DI to final rinse	Investigate softening when hardness is persistently >150 mg/L as CaCO ₃ ; trend nozzle pressure and filter differential pressure
Oil, sand and dust loading	Screen + grit trap/settlement + oil-water separator before fine filtration	Remove solids/oil before membranes; inspect/purge separators on a fixed schedule
Membrane fouling / high RO reject	Use staged pretreatment and treat only the high-quality fraction with UF/RO	Measure kWh/m ³ and reject ratio; avoid polishing all recycled water
Poor reclaimed-water quality / odor	Provide aeration/oxidation or validated disinfection and controlled tank turnover	Turbidity/conductivity + periodic laboratory verification; no stagnant tanks

Leaks and excessive nozzle flow	Zone metering, pressure regulation, nozzle maintenance, automatic leak alarms	Compare L/vehicle by wash recipe; investigate deviations >10% from commissioned baseline
Unclear benefits after automatic conversion	Commission water and energy performance before/after retrofit	Report freshwater L/vehicle, recycle %, kWh/vehicle, downtime and water-quality compliance

Table 2. Core performance indicators for facility-level water-energy governance.

KPI	Unit / definition	Primary decision use	Suggested data source
Freshwater intensity	L/vehicle = incoming freshwater / vehicles washed	Track direct water demand and compare wash programs	Main water meter + vehicle counter
Recycle ratio	% = reclaimed water reused / total wash water applied	Assess circularity while checking quality and energy consequences	Reclaimed-flow meter + total applied-flow estimate
Electricity intensity	kWh/vehicle = facility electricity / vehicles washed	Identify whole-site energy drift, including wash and treatment loads	Submeter or utility meter + vehicle counter
Specific treatment energy	kWh/m ³ reclaimed water produced	Compare reclamation modes and detect fouling or inefficient pressure	Treatment submeter + reclaimed-water production meter
Reject blowdown ratio	% of treated feed not returned to reuse	Expose water loss from membranes, purges and quality control	Reject meter or tank balance
Quality compliance rate	% samples / online intervals meeting reuse-stage limits	Prevent efficiency gains from compromising wash or hygiene requirements	Turbidity/conductivity/disinfection sensors + laboratory checks
Chemical intensity	g or mL/vehicle, by chemical	Link dosing to throughput and avoid overdosing	Dosing-pump logs + vehicle counter
Unplanned downtime	h/month attributable to water or treatment system	Connect reliability with sustainability and maintenance quality	CMMS / operator logs

X. LIMITATIONS

This review is limited by the small number of recent studies measuring energy directly in car-wash treatment, the heterogeneity of wastewater characteristics and wash practices, and the scarcity of peer-reviewed Saudi facility data. Transfer from municipal wastewater and desalination literature was therefore restricted to operational principles rather than numerical performance claims. The review is integrative, not a registered systematic review or meta-analysis, so it does not claim exhaustive coverage or pooled effect sizes. Economic outcomes are also site-specific because tariffs, throughput, equipment age, water source, and disposal conditions vary. The framework should therefore be validated through Saudi pilot and commercial-site measurements before adopting prescriptive thresholds. The revised estimate of active car-wash locations is based on a commercial directory, not an official Saudi licensing register, and the national water-use estimate is a scenario calculation based on published wash volumes and international water-intensity ranges; it should not be interpreted as an audited national consumption statistic.

XI. CONCLUSION

Automated car-wash sustainability in Saudi Arabia should be implemented as a water-quality-controlled recycling system, not simply as a change from hand washing to automatic machinery. The most actionable solution is a staged architecture: (1) meter water by wash zone; (2) remove grit, sand and free oil before treatment; (3) segregate and recycle suitable streams to prewash, wheels, underbody and brush stages; (4) condition hard water before scale-sensitive equipment; (5) reserve RO/DI-quality water for the final spot-free rinse; and (6) control the system using flow, turbidity/conductivity, pressure and differential-pressure alarms. Where site conditions permit, a 70-80% recycle objective and freshwater intensity of approximately 40-60 L per passenger vehicle provide practical design targets to be validated during commissioning rather than assumed as universal regulatory limits.

The regulatory transition at Saudi fuel stations creates an opportunity to lock these practices into new automatic-wash installations. The principal risk is that automatic equipment is installed without adequate pretreatment or water conditioning, causing limescale, clogged nozzles, higher pump energy, membrane fouling, pipe restriction and downtime. Saudi source-water variability makes hardness/TDS testing essential; softening should be evaluated where hardness is persistently high, while high-grade RO treatment should be limited to the fraction that actually needs it. A national performance approach should therefore track freshwater L/vehicle, recycle ratio, kWh/vehicle, treatment kWh/m³, reject ratio, hardness/TDS, quality compliance and scale-related downtime. Because no official national car-wash water inventory is publicly available, the indicative sector figures in this review should be used to motivate metering and reporting, not as compliance statistics. The decisive recommendation is to make water recycling and water-quality management integral to every automatic fuel-station car-wash conversion so that regulation produces verified freshwater savings and reliable equipment operation.

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