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Research article

Diagnosis-driven recovery of an oily wastewater treatment plant: Cutting external disposal and improving operational performance in a petrochemical complex

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Abstract: Oily effluent treatment is a critical service for the safe, compliant and sustainable operation of petrochemical complexes. This work presents the diagnosis and recovery program of the oily wastewater treatment plant (locally designated "OILY") of a petrochemical complex in the south of the province of Buenos Aires, Argentina, a two-train physical–mechanical system (gravity/centrifugal primary separation, sand–anthracite coalescing filtration, and gas-stripping tertiary separation) with a nominal capacity of 25 m^3/h per train. At the start of the study, the unit operated well below design, with recurrent out-of-specification inlet events, premature filter saturation, high differential pressure across the coalescing beds, chronic failures of the on-line total organic carbon (TOC) analyzer, a control-logic flaw in the distributed control system that could trigger relief-device activation, and weak operational discipline. A structured methodology combining historical trend analysis, field surveys, expert interviews, and review of computerized maintenance management records was applied to identify root causes and to prioritize corrective actions. Implemented measures included reinforced sampling routines and operational discipline, correction of the control logic, a prioritized equipment-reliability list, internal steam cleaning of plugged equipment and lines, and updated operating procedures; additional structural actions (coalescing-media replacement and TOC-analyzer upgrade) are in progress. In 2025, the mass of oily water sent to external treatment was 24.2% lower for Cracker 1 and 4.4% lower for Cracker 2 than in 2024, with an associated realized saving of approximately USD

3,588. Under restored design operation, the projected gross avoided-disposal benefit is nearly USD 21,100 per year; capital and incremental internal operating costs are not included in this screening estimate. The case illustrates how a diagnosis-driven recovery program can improve the operational and environmental performance of existing industrial treatment assets and contribute to more sustainable and resilient operation, consistent with key Industry 5.0 principles.

Keywords: Industry 5.0; circular economy; oily wastewater treatment; coalescing filtration; process reliability; petrochemical effluents; total organic carbon; chemical oxygen demand; operational discipline

1. Introduction

The efficient management of industrial effluents is one of the cornerstones for ensuring the environmental sustainability of production operations [1,2]. In petrochemical complexes, oily wastewater treatment plays a strategic role in mitigating the impacts of chemical processes, ensuring that liquid residues are treated in accordance with applicable environmental standards before discharge or reuse.

The concept of Industry 5.0 has emerged as an evolution of the digitalization and automation paradigms of Industry 4.0, adding a vision centered on people, environmental sustainability, and the resilience of production systems [3,4]. The diagnosis and recovery of critical treatment units is a concrete application of these principles, combining asset reliability, effluent quality control, and standardized operating practices [5]. In the petrochemical sector in particular, the literature shows that effluent treatment has gained increasing relevance because of the presence of persistent organic compounds and rising environmental requirements, driving more efficient treatment technologies and management strategies [6].

Over recent years, several operational and structural deficiencies were identified in the oily wastewater treatment plant (locally designated “OILY”) of a petrochemical complex in the south of the province of Buenos Aires, Argentina, which compromised its performance and prevented it from reaching design conditions. When the unit cannot condition the effluent to discharge specification, the effluent must be sent to external treatment companies at a very high cost. This situation motivated a comprehensive recovery plan comprising corrective actions on critical equipment, adjustment of inlet parameters (chemical oxygen demand, pH, temperature), revision of analytical systems, and redefinition of control strategies, with the objective of restoring system reliability and guaranteeing treated-effluent quality.

The general objective of this work is to demonstrate the applied engineering knowledge used to address this problem by identifying the root causes of the low performance; defining and implementing prioritized corrective actions; and evaluating the operational, environmental, and reliability impact. The study also aims to provide a reference framework for future interventions in industrial effluent treatment systems, promoting a culture of environmental responsibility and operational excellence.

Unlike studies focused primarily on the development or comparison of new wastewater-treatment technologies, this work addresses the recovery of an existing full-scale industrial treatment unit under real operating constraints. Its main contribution is the integration of process diagnosis, maintenance and instrumentation assessment, operational knowledge, corrective-action prioritization, and

performance monitoring into a diagnosis-driven recovery approach that can be adapted to similar industrial wastewater facilities.

2. Related work

The treatment of petroleum-industry and petrochemical effluents has been extensively reviewed in the literature. Comprehensive reviews describe the wide variety of pollutants present in these streams (petroleum hydrocarbons, oil and grease, phenols, mercaptans, ammonia, and sulfides) and classify the available technologies into physical, chemical, and biological processes, frequently combined into hybrid trains for low-biodegradability wastewater [7]. In practice, the primary stage of refinery and petrochemical effluent treatment still relies predominantly on physical–mechanical operations, such as API and inclined-plate separators, dissolved-air flotation, and coalescing media, which exploit density differences and droplet coalescence to remove free and dispersed oil before any downstream polishing [8]. Bibliometric analyses confirm that research interest in petrochemical wastewater treatment has grown markedly over the last two decades, driven by tighter environmental legislation and by the persistence of recalcitrant organic compounds [6]. Optimization-based approaches have also been proposed to support the design and operation of treatment systems, such as bi-objective cost-performance analysis of physicochemical phosphorus-removal configurations [9]. Most of this body of work, however, focuses on developing or comparing novel and advanced treatment technologies rather than on recovering and sustaining the performance of an existing physical–mechanical installation under real industrial constraints.

A second, largely separate stream of literature addresses the reliability and maintenance of process and water-treatment assets. Reliability-centered maintenance (RCM) and lean-maintenance frameworks provide structured methods to identify failure modes, prioritize critical equipment, and define preventive tasks that improve availability while controlling cost [10,11]. Recent case studies have applied these ideas specifically to wastewater treatment plants: opportunistic grouping of preventive-maintenance interventions on critical high-risk assets has been shown to reduce system inefficiency by about 26% and to increase asset availability [12]; criticality analyses based on reliability and failure-propagation effects have been used to rank equipment and target interventions in complex treatment plants [13]; and optimization frameworks for opportunistic preventive-maintenance planning have demonstrated measurable reductions in the number of stoppages [14]. Complementary to physical-maintenance planning, data-driven and lean-digital approaches are increasingly used to support industrial operations and asset management: machine-learning models have been applied to predict equipment-inspection times in hydrocarbon-tank maintenance [15]; lean principles combined with digital traceability have reduced work-in-process and defects in manufacturing support areas [16]; and multi-objective optimization and scheduling methods have been used to plan complex industrial operations [17]. These studies consistently report that concentrating maintenance effort on critical assets and reinforcing operational discipline yields tangible availability and cost benefits.

While both bodies of work, effluent-treatment technology on the one hand and asset reliability and maintenance on the other, are well developed individually, comparatively few studies report their integration: the recovery of an under-performing industrial oily-effluent unit through a diagnosis-

driven program that combines reliability engineering, control-logic correction, and operational discipline with quantified environmental and economic outcomes and that is framed within the human-centric, resilient, and sustainable vision of Industry 5.0 [3–5]. The present case study addresses this gap by documenting such an intervention in a full-scale petrochemical effluent treatment plant.

The novelty of this work lies not in proposing a new wastewater-treatment technology but in systematizing the recovery of an existing full-scale industrial treatment unit under real operational constraints. The study integrates process diagnosis, maintenance and instrumentation assessment, operational knowledge, corrective-action prioritization, and post-intervention performance monitoring into a single recovery approach.

3. Materials and methods

3.1. Description of the treatment plant

The OILY plant removes hydrocarbons from contaminated water coming from the process area, flare, hydrocarbon storage, and equipment washing of the two ethylene crackers of the site (designated Cracker 1 and Cracker 2). The contaminated water carries three types of hydrocarbons (settleable, emulsified and dissolved) [18–21], which are removed in three sequential stages:

- Primary separation: settleable hydrocarbons and solids are removed by gravity, centrifugal force, and an inclined-plate pack in vessel V-9602; light oil and gasoline are collected at the top and sent to the slop tank, while heavy material is withdrawn from the conical bottom for external disposal. Pre-treated water is stored in feed tank D-9601.
- Secondary separation: water is pumped through a sand–anthracite coalescing filter (V-9603/B) operated flooded; the oleophilic medium promotes droplet coalescence so that the oil floats and is removed. The automatic backwash sequence is initiated when the differential pressure (ΔP), measured by PDIT-96030/B, reaches 0.42 kg/cm². The 0.50 kg/cm² value corresponds to the upper allowable operating/protection criterion for the filters and should not be interpreted as the automatic backwash set point. A separate independent ΔP alarm threshold was not identified in the plant documentation available for this study; therefore, no additional alarm value is reported.
- Tertiary separation: dissolved hydrocarbons are stripped in packed columns T-9604/B using fuel gas or nitrogen in counter-current, and the stripped gas is recovered to the fuel-gas header. Each column is approximately 0.64 m in diameter and 20 m high and contains two packed sections with 1-in stainless-steel Flexiring-type rings and a top demister. Liquid flow is governed by the nominal treatment rate of each train (up to 25 m³/h). Gas flow is ratio-controlled against liquid flow, with a design gas/liquid mass ratio of approximately 0.044–0.045 kg gas/kg water, adjustable up to 0.06 without column flooding [25]. Under normal fuel-gas operation, top pressure is approximately 4 kg/cm². The design basis targets an outlet BTX concentration of 50 µg/L (50 ppb) from an inlet design concentration of approximately 1344 ppm. These values characterize the design basis of the tertiary stage and should not be interpreted as a measured pre/post removal efficiency in the present study.

The unit comprises two parallel treatment trains (Figure 1) and is operated through seven sequenced steps of a distributed control system (DCS).

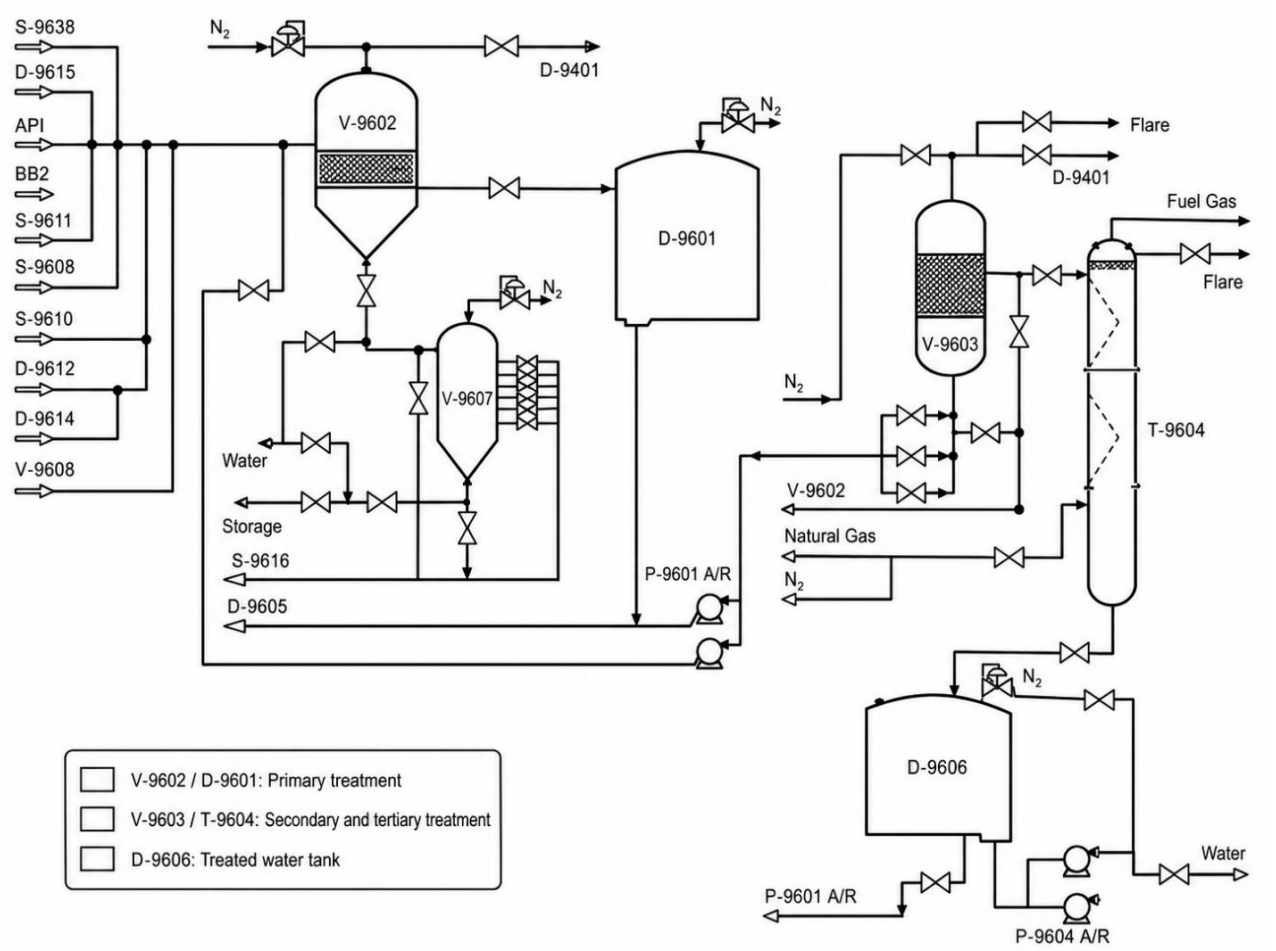


Figure 1. Schematic of one OILY treatment train (primary, secondary and tertiary separation).

The sequences that enable the operation of the OILY plant, commanded by the MOD5 control system, are:

- Awaiting maintenance: In this step, all equipment is in its fail-safe state. No actions are performed by the MOD5 system.
- Awaiting orders: In this step, the equipment is prepared to transition to either process standby or awaiting maintenance.
- Process standby: In this step, the equipment is ready for normal operation.
- Filling D-9601: In this step, filling of tank D-9601 with water coming from the collection basins is enabled. Pump P-9601 does not run to send water to treatment.
- V-9602 primary peprocessing: In this step, water recirculation from D-9601 to V-9602 is carried out for two different purposes:
    - Prior to sending to treatment: To remove oils and solids contained in D-9601. This step occurs at a significantly lower level than what is required to start treatment, ensuring sufficient recycle, considering that it will be interrupted during filter washing.
    - During filter washing: Recirculation is carried out if filter V-9603 A/B backwashing is in progress.

- V-9603 verification Δ P and V-9602: In this step, water recirculation from D-9601 through V-9603 to V-9602 is performed. The MOD5 automatically executes the following actions: disables recirculation to V-9602 and keeps P-9601 A/B/R running, ramping up their flow rate up to 25 m³/h.
- Secondary/tertiary treatment: Water is sent to V-9603 for treatment using P-9601, recirculation to V-9602 is disabled, and filling of D-9601 is enabled if its level is below 80% or if draining any of the treatment basins is required. Hydrocarbon/water interface level control and V-9602 purging are also enabled.

Figure 2 presents a visual summary of sequences that enable the operation of the OILY plant.

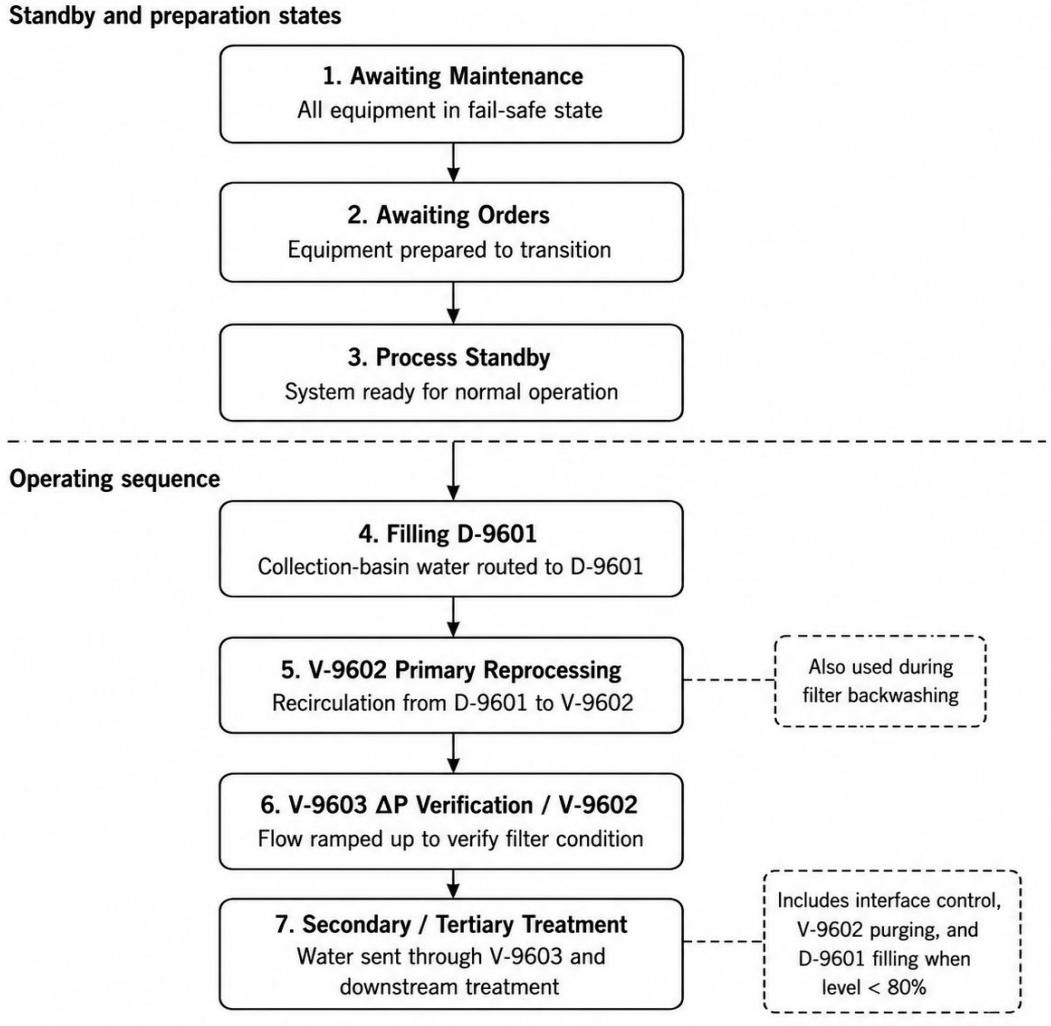


Figure 2. Simplified MOD5 control sequence for the OILY plant, showing the standby/preparation states and the main operating stages of the treatment process. Dashed boxes indicate complementary actions associated with filter backwashing and secondary/tertiary treatment.

The nominal downstream treatment capacity is 25 m³/h per train (50 m³/h with both trains in parallel), whereas the 90 m³/h value for V-9602 is an upstream hydraulic limit and is also relevant

during filter backwashing; it is not a continuous feed rate to the secondary and tertiary stages. Hydraulic decoupling is provided mainly by feed tank D-9601 and the sequence logic. The first treatment train starts at approximately 30% D-9601 level and the second train starts if the level rises to approximately 60%; both trains stop at about 15% level. A high-level alarm is provided at 75%, and a very-high-level protection at 85% blocks additional inflow. During coalescing-filter backwashing, new quench and collection-pit streams are not admitted to the OILY train and the backwash stream is returned toward V-9602. Under normal treatment, each secondary/tertiary train therefore remains limited to its 25 m^3/h design flow. The available plant documentation did not provide a validated D-9601 working-volume value suitable for reporting, so the buffering function is described through the documented operating-level logic rather than an unsupported tank-volume estimate.

Tank D-9606 separately stores off-specification treated water for later reprocessing, preventing this inventory from being immediately recirculated through the downstream trains. Treated water is monitored continuously at the common outlet by an on-line total organic carbon (TOC) analyzer (two-stage advanced oxidation type): below 5 mg/L the effluent is considered on-specification and routed to the final tank D-9607 for discharge, whereas above 5 mg/L it is sent to tank D-9606 for reprocessing.

The inlet stream is considered suitable for internal treatment in the OILY unit when its COD is between 250 and 750 mg/L; its pH is between 6.5 and 10; and it is free of glycol, caustic, amines, methanol, dicyclopentadiene, and solvesso. Streams with COD below 250 mg/L are already within the COD discharge specification, whereas streams above 750 mg/L or containing incompatible compounds are considered unsuitable for direct treatment in the unit because they may overload the coalescing beds and impair separation performance. The treated effluent must comply with the discharge specifications established for the site, including TOC < 5 mg/L, COD < 250 mg/L, pH between 6.5 and 10, total hydrocarbons < 10 mg/L, suspended solids < 10 mg/L, and BTX < 50 µg/L [22]. Since COD determination requires approximately three hours of laboratory analysis, the on-line TOC signal is used as a real-time operational indicator to support routing decisions between discharge and reprocessing, following standardized total organic carbon measurement procedures [1]. This use of TOC does not replace COD verification because the COD/TOC relationship is matrix-dependent; therefore, the correlation must be established for the specific wastewater stream and recalibrated whenever significant changes in water composition occur [23,24].

The COD–TOC relationship used for operational decision-making was established following the analyzer manufacturer's methodology using simultaneous COD and TOC measurements from the same wastewater stream. The resulting relationship was considered applicable only to the specific oily-water matrix under study and was not assumed to be universal. Because the available plant documentation does not contain a complete paired-sample dataset and regression statistics suitable for independent validation, the present study does not report a regression equation or correlation coefficient. This represents a limitation of the current operational monitoring strategy. In practice, recalibration is required whenever the influent composition changes significantly. Table 1 summarizes the detailed parameters for the influent and setting conditions.

Table 1. Parameters for the influent and setting conditions.

Category/Phase	Parameter/Condition	Specification Value/Operating Range
Influent specification (entry)	Chemical oxygen demand (COD)	250 mg/L < COD < 750 mg/L
	pH	6.5 < pH < 10
	Prohibited substances/restrictions	NO glycol, caustic, amines, methanol, dicyclopentadiene, or solvesso allowed.
	Treatment type	Physical-mechanical (coalescence + filtration); does not handle complex or highly reactive solubilized organic compounds.
Effluent specification (outlet)	Total organic carbon (TOC; in-line analyzer)	< 5 mg/L for transfer to Tank D-9607/Gauging. (> 5 mg/L it is sent to D-9606 for reprocessing).
	Outlet temperature (discharge to gauging)	< 45 °C (Legal limit per Law 5824/Decree 21070/6; additionally, T > 60°C degrades the FRP material of tank D-9607).
	COD limit	≤ 250 mg/L
	BOD limit	≤ 50 mg/L
	Oils and greases	≤ 15 mg/L
	Total hydrocarbons (gauging)	≤ 10 mg/L
Key operating data and conditions	Nominal treatment flow rate	25 m^3/h per train (batch operation mode).
	Train configuration	2 parallel trains for secondary and tertiary separation.
	Automatic backwash set point	$\Delta P = 0.42$ kg/cm^2 (PDIT-96030/B); initiates the automatic backwash sequence.
	Upper allowable ΔP/protection criterion	$\Delta P < 0.50$ kg/cm^2; upper operating/protection threshold for V-9603 A/B.
	Independent ΔP alarm limit	No separate independent alarm threshold was identified in the plant documentation used for this study.
	Filter backwash flow rate	Up to 90 m^3/h in the existing system. The supplier-recommended design flow is 102.5 m^3/h; the lower available flow is compensated by a longer backwash duration.
	Gas-stripping design conditions	Liquid flow up to 25 m^3/h per train; gas/liquid mass ratio ≈ 0.044–0.045 kg/kg, adjustable up to 0.06; top pressure ≈ 4 kg/cm^2 under normal fuel-gas operation.
	Gas-stripping internals/BTX design basis	Two 1-in stainless-steel Flexiring packed sections plus top demister; design BTX basis: ≈ 1344 ppm inlet to 50 µg/L (50 ppb) outlet.
	Gauging pump operation (P-9604 A/B/R)	- 1st pump start: at 25% level in D-9607. - 2nd pump start: if level reaches 30%. - Pump stop: low-level cutoff at 10%.
	Control system	Automated sequences managed by the MOD5 control system.

3.2. Diagnostic and intervention methodology

To identify the root causes of the low performance, historical process trends were analyzed and compared against design conditions. Plant walkdowns and structured interviews were conducted with operators, board operators, shift coordinators, former production engineers, and technical analysts in order to consolidate knowledge of periods in which the plant had operated at maximum rate. From the engineering and maintenance side, recurrent-failure instruments were identified and the work orders recorded in the computerized maintenance management system (CMMS) were reviewed together with their technical reports in periodic meetings with reliability, maintenance, improvement, and project engineers.

On the basis of this diagnosis, deficiencies were classified and prioritized using a qualitative red/amber/green criticality scheme and translated into corrective actions. The classification was based on multidisciplinary engineering judgment considering four dimensions: (i) process safety and potential personnel consequence; (ii) environmental and discharge-compliance consequence; (iii) operational impact on treatment capacity, continuity and availability; and (iv) recurrence or likelihood as evidenced by process trends, alarms, maintenance records, and field observations. High/red items were those with a direct safety or environmental consequence or the potential to cause a major loss of treatment capability and therefore required prompt action. Medium/amber items represented significant degradation or maintenance burden requiring planned intervention, while low/green items had lower immediate consequence and were mainly addressed through procedural, monitoring, or organizational improvements. Cost was not used to reduce the criticality assigned to a hazard; rather, it was used to sequence alternatives among issues of comparable criticality, prioritizing low-cost/high-impact operational and control measures before capital-intensive interventions.

The operational comparison was established using historical process trends and operating records. Records from 2022 were reviewed to provide broader historical context, while the formal hydraulic before-and-after comparison focused on two periods: 2023–early 2024 for the pre-intervention condition and mid-2024–2025 for the post-intervention condition. Annual off-site treatment volumes were analyzed separately for 2023–2025 because these data were available as yearly totals rather than for the same hydraulic comparison windows.

The intervention was progressive rather than a single commissioning event. During the mid-2024–2025 implementation window, the main low-cost measures included reinforced per-shift sampling and operating routines, DCS logic corrections and feed-quality interlocks, tank-level surveillance and alarms, the field survey and prioritization of equipment and instrument repairs, sludge-draining and cleaning routines, and updates to operating procedures and training. Steam-cleaning activities were initiated during the post-intervention period and remain in progress. Coalescing-media replacement remains pending, while the TOC-analyzer upgrade/fast-loop alternative remains under analysis. Exact day-level commissioning dates were not consistently recoverable for every action from the retrospective records; consequently, the verified implementation window and current status are reported rather than unsupported exact dates.

For the hydraulic assessment, the baseline was characterized by short coalescing-filter runs and rapid differential-pressure buildup, whereas the post-intervention condition reflects operation after implementation of the main operational, control, and maintenance measures. The analysis focused on

representative filter run length and ΔP buildup rate. The historian records were not stored as a complete cycle-indexed experimental dataset; therefore, an auditable total number of individual operating cycles, cycle-by-cycle ranges, standard deviations, and confidence intervals cannot be reported. Figure 6 should consequently be interpreted as a synthesis of representative operating behavior from the available historian records rather than as six independent measured cycles.

Table 2 summarizes the temporal structure of the study. The detailed action-by-action implementation window and current status are also reported in Table 3.

Table 2. Timeline of data windows and implementation stages of the recovery program.

Period	Role in the study	Main actions/data status
2022	Historical context	Historical trends reviewed; not part of the formal hydraulic pre/post comparison.
2023–early 2024	Pre-intervention baseline	Baseline hydraulic behavior and diagnosed deficiencies.
Mid-2024–2025	Progressive implementation and post-intervention assessment	Sampling/operating routines, DCS logic and feed-quality controls, surveillance/alarms, field repair prioritization, cleaning/purge routines, and procedure/training updates progressively implemented; steam cleaning initiated. Structural media replacement remained pending and the TOC-analyzer/fast-loop alternative remained under analysis at study closure.

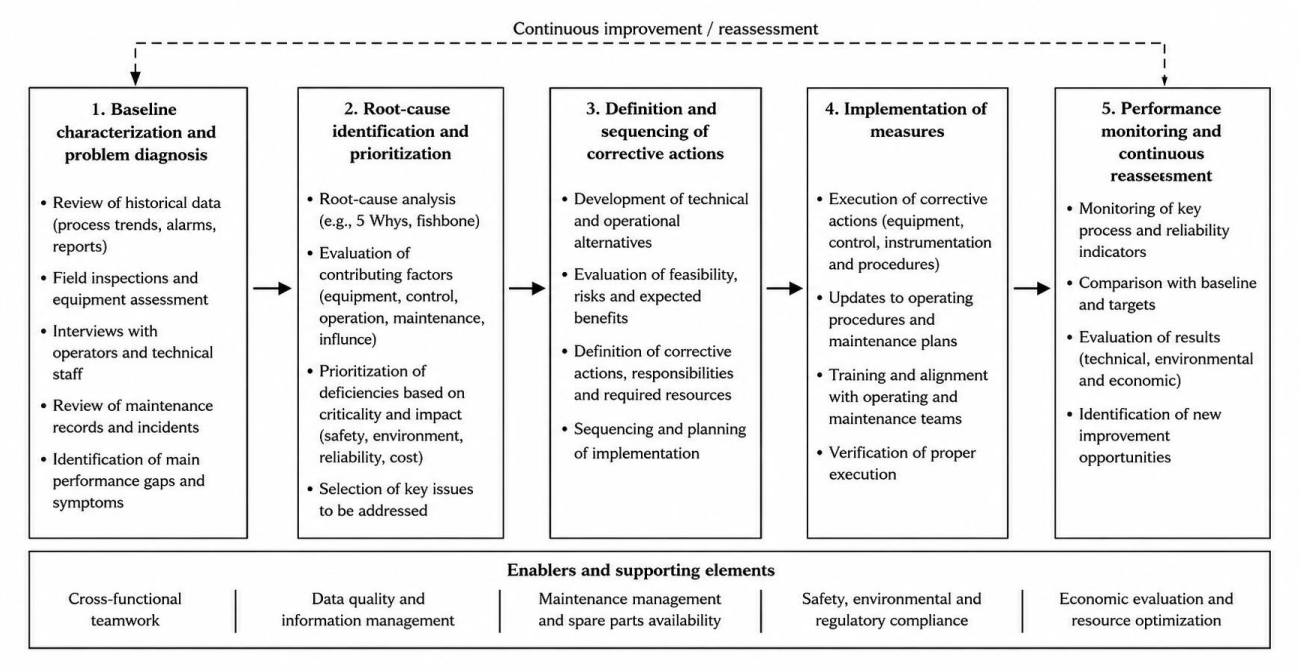


Figure 3. Diagnosis-driven recovery framework applied in this study. The dashed arrow represents the feedback loop for continuous improvement and reassessment.

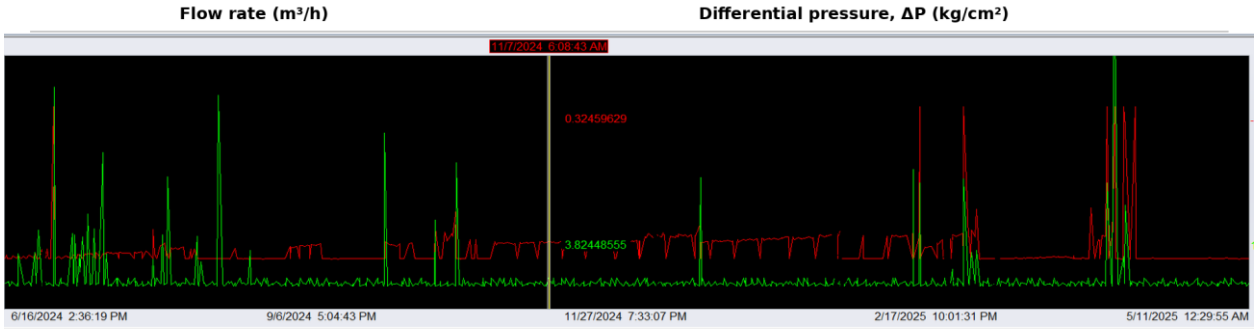
Based on the intervention, a transferable diagnosis-driven recovery framework is proposed for similar industrial wastewater facilities, consisting of five stages: (1) baseline characterization and problem diagnosis; (2) root-cause identification and prioritization; (3) definition and sequencing of corrective actions; (4) implementation of operational, control, and maintenance measures; and (5) performance monitoring and continuous reassessment. This framework is summarized in Figure 3.

4. Results

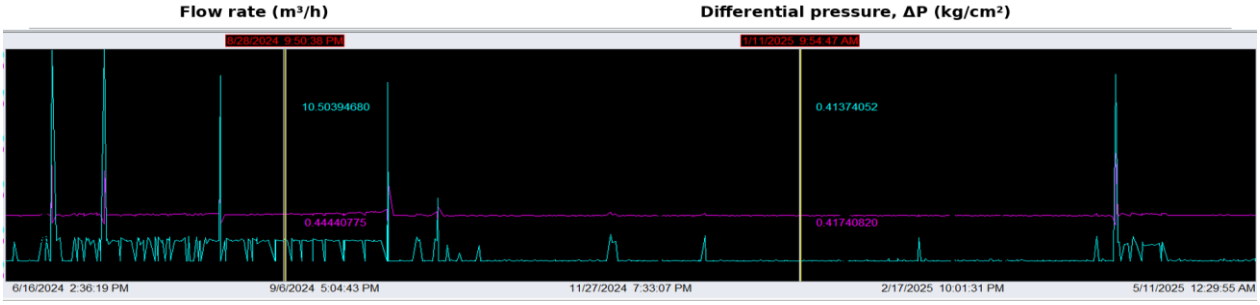
4.1. Diagnosed deficiencies (baseline condition)

At the start of the study the plant operated well below design, with multiple out-of-specification inlet events (particularly from Cracker 2), indicating deficiencies in both primary and secondary separation, with bed degradation, line plugging, and high external-treatment costs. The main deficiencies identified were the following.

- High ΔP and premature saturation of the coalescing filters: Even at flows well below the 25 m³/h design rate, ΔP across V-9603/B remained close to the backwash set-point and increased over time (Figure 4), evidencing severe fouling of the media and likely solidified-hydrocarbon plugging in equipment and process lines. The ΔP also stayed high (≈0.41 kg/cm²) with no through-flow, pointing to plugging and/or a faulty/obstructed instrument tap.



(a) Coalescing filters V-9603



(b) Coalescing filters V-9603B

Figure 4. Inlet flow versus differential pressure (ΔP) trends across the coalescing filters of the two trains, (a) V-9603 and (b) V-9603B, showing high ΔP at sub-design flow.

- Plugging of bottom lines and valves: During a maintenance handover, the V-9603 vessel could not be drained; trend analysis (constant V-9602 inlet flow, negligible V-9603 level drop and persistent pressurization above the starting value) confirmed a partially blocked outlet path rather than an instrument fault, after field verification of valve alignments.
- Chronic failures of the on-line TOC analyzer: The analyzer (AIT-96070) at the final tank D-9607 failed recurrently, forcing manual sampling and delaying reprocessing or discharge. It was concluded that the technology was not well suited to the plant's batch operation, because continuous sample flow is required and the dirty, variable matrix damaged internal components.
- Control-logic flaw in the DCS: On overfilling of V-9602, the original logic closed the outlet valve instead of the inlet valve, pressurizing the vessel and activating its pressure-safety valve set at 3.5 kg/cm² (Figure 5).

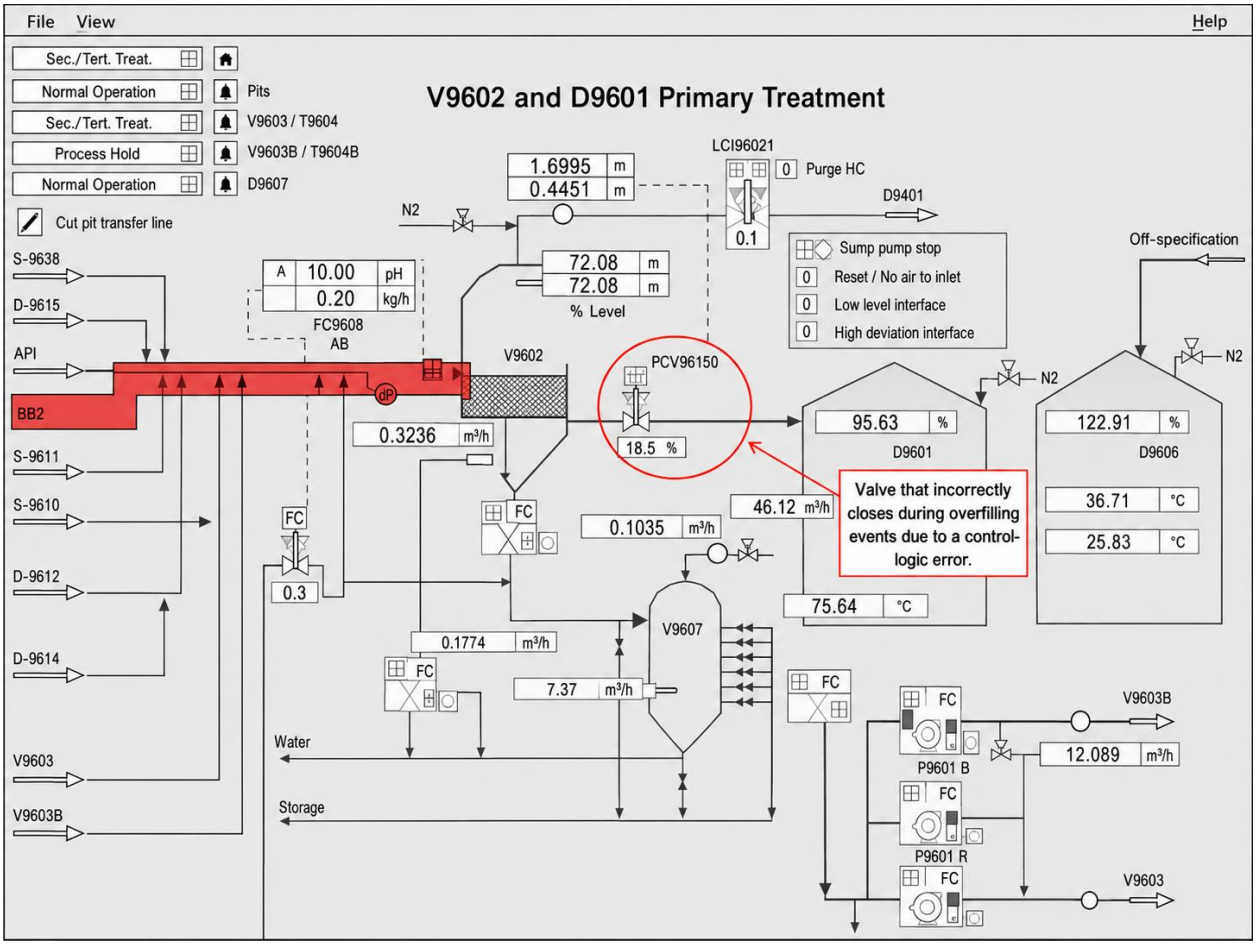


Figure 5. DCS control screen showing the overpressure/relief event associated with the original V-9602 logic.

- Equipment and instrumentation deficiencies: Field surveys of pumps, control and self-regulating valves, and level instruments revealed sticking, mismatches between field sight-glasses and the control system and seal leaks. Maintenance-record review and field assessment also indicated

gaps in the execution of preventive-maintenance plans, which were associated with recurrent equipment and instrumentation deficiencies.

- Weak operational discipline: Structured cleaning, sampling, sludge-draining, and preventive-purge routines were largely absent, leading to deposit build-up, hydraulic imbalances, overfilling risk, and loss of separation efficiency; operating procedures were also outdated.
- Accumulation of out-of-specification effluent: Large volumes of off-spec water accumulated in tank D-9606, reducing operating flexibility, increasing energy and chemical use, and ultimately requiring costly external disposal.

4.2. Corrective actions

A set of prioritized corrective actions was defined to restore the nominal capacity and reliability of the unit. Operational and control measures were implemented first because of their low cost and immediate impact: reinforced once-per-shift sampling routines loaded into the mobile task-list tool, automatic alarms and interlocks on the Cracker 2 quench feed (e.g., removing the send permissive below 100 °C), correction of the DCS valve-closure logic, a prioritized equipment-reliability repair list, sludge-draining and cleaning routines, and updated operating procedures. Internal and external steam cleaning of plugged equipment and lines was started to soften and displace solidified hydrocarbons, a method preferred over air or mechanical cleaning because it avoids flammable atmospheres and thermal shock. Two structural measures remain in progress: complete replacement of the coalescing media (subject to tender and economic analysis) and either an upgrade of the TOC analyzer to a more robust two-stage advanced-oxidation technology or installation of an auxiliary fast-loop recirculation pump to provide continuous sample flow.

The suitability of an online TOC analyzer for oily wastewater depends not only on the oxidation principle employed, but also on the design of the sample handling, sample conditioning, tubing, reactor and cleaning systems. Two-stage advanced oxidation (TSAO) is not intrinsically unsuitable for oily wastewater; however, different TSAO analyzers are designed for different sample matrices and operating conditions. More compact or less sophisticated configurations may be intended for relatively clean process or effluent water and may require stable sample flow, filtration or additional sample conditioning. Under these conditions, the presence of dispersed oil, grease, and small suspended particles can progressively contaminate or obstruct the sample path, resulting in unstable measurements, increased maintenance requirements, and analyzer downtime. Difficult wastewater matrices can also generate oil accumulation on wetted surfaces and sample-line components, while intermittent or insufficient sample flow can prevent representative sampling and interfere with the regular analytical cycle. Similar limitations are recognized for online TOC monitoring in difficult wastewater matrices, where suspended solids, oils, and turbidity can complicate sample delivery and measurement reliability.

For this reason, the main limitation identified in the present case was not the TSAO oxidation principle itself but the mismatch between the existing analyzer configuration and the operating conditions of the OILY plant. The wastewater matrix is variable and may contain traces of hydrocarbons and small solid particles, while the plant does not always provide the stable, continuous sample flow required by the existing analyzer configuration. Under these conditions, interruptions in

sample availability can result in repeated analyzer failures and loss of reliable online TOC information, forcing operators to rely on manual sampling and laboratory COD analysis.

A more robust online analyzer would therefore require an integrated sampling and conditioning system specifically designed for difficult industrial wastewater. Relevant features include oversized sample tubing, tolerance to suspended particles without fine pre-filtration, automatic cleaning of the sample line and reactor, resistance to oil and grease accumulation, reliable sample-flow detection, and rapid recovery following high organic-load events [28]. Industrial-grade TSAO systems incorporating these features are specifically designed for wastewater containing oils, fats, greases, sludge, and suspended particles; some configurations can handle particles up to approximately 2 mm without pre-filtration and incorporate automatic cleaning of the sample path and reactor [29].

Therefore, the proposed analyzer upgrade should not be understood simply as a change from TSAO to another oxidation principle. Rather, it represents a transition to a more robust analyzer configuration adapted to the actual OILY wastewater matrix and operating conditions capable of maintaining representative sampling and reliable online measurement despite intermittent flow, oil contamination, and small particulate loads. This distinction is important because a more sophisticated TSAO analyzer can provide reliable operation in oily wastewater when the oxidation system is combined with appropriate sample-handling and self-cleaning technologies. Table 3 summarizes the actions and their status.

Table 3. Diagnosed problems, proposed corrective actions and implementation status.

Problem/axis	**Root cause**	**Criticality**	**Proposed action**	Status/implementation window	**KPI**	Observed/expected impact
Saturation and high ΔP in coalescing filters V-9603 A/B	Heavy fouling from organic buildup and solidified hydrocarbons.	High (red)	Internal steam cleaning of equipment and lines to release solidified hydrocarbons	Mid-2024–2025; in progress	Coalescing bed Δ P and run length.	Reduced ΔP buildup rate by 59% and extended the representative run length from approximately 5 to 12 days.
Saturation of filter media	Long-term accumulation of non-removable hydrocarbons and particulate clogging.	High (red)	Complete replacement of the coalescing media in V-9603 A/B	Not implemented; future	Filter hydraulic capacity restoration	Target capacity recovery to design flow of 25 m^3/h
Plugging of bottom lines and valves	Solidification of heavy hydrocarbon fractions	Medium (amber)	External steam cleaning to	Mid-2024–2025; under development	Drain rate and vessel pressure stabilization	Restoration of gravity draining and elimination of

Problem/axis	**Root cause**	**Criticality**	**Proposed action**	Status/implementation window	**KPI**	Observed/expected impact
	during off-line or low-flow conditions.		release obstructions		during maneuvers.	unexpected vessel pressurization.
Unreliable COD/TOC correlation (analyzer failures)	Continuous sample flow requirements damaged by dirty, variable batch matrix in analyzer AIT-96070.	High (red)	Evaluate TSAO analyzer upgrade or auxiliary fast-loop recirculation pump	Not implemented; under analysis	On-line analyzer uptime and manual sampling frequency.	Expected elimination of manual sampling delays and direct control of automated discharge/reprocess routing.
Off-spec feed to OILY from Cracker 2	Temperature drops below 100 °C and surges of incompatible chemicals (caustics, solvesso).	High (red)	Reinforced operational discipline, per-shift sampling, automatic alarms	Mid-2024–2025; implemented	Out-of-specification inlet stream events.	Reduced off-spec feed instances
DCS logic causing overfilling/relief activation	Control code closed the vessel outlet instead of the inlet during V-9602 overfill events.	High (red)	Correction of valve-closure logic and control adjustment	Mid-2024–2025; implemented	Pressure-safety valve (PSV) relief activations.	Eliminated overpressure relief events at V-9602.
Pump, valve and instrument deficiencies	Deferred maintenance, seal leaks, sticking valves, and sight-glass mismatches.	Medium (amber)	Full field survey + prioritized repair list	Mid-2024–2025; implemented	Backlog of critical instrumentation CMMS work orders.	Improved operating condition of prioritized pumps, control valves, and level instruments.
Lack of internal cleaning routines	Missing structured operator tasks for	Medium (amber)	Draining, purge and cleaning routines	Mid-2024–2025; implemented	Execution of scheduled draining, purge, and	Improved control of solid-deposit buildup and consistency of

Problem/axis	**Root cause**	**Criticality**	**Proposed action**	Status/implementation window	**KPI**	Observed/expected impact
	regular purging and sludge removal.		loaded in MTL		cleaning routines.	primary-separation operation.
Lack of sampling routines	Absence of mandatory shift-wise monitoring routines.	Low (green)	Per-shift sampling + 24 h laboratory contract	Mid-2024–2025; implemented	Sampling schedule compliance and analytical turnaround time.	Rapid identification of off-spec parameters before bed contamination occurs.
Outdated procedures	Operating manuals were non-reflective of current control logic and sequencing.	Low (green)	Update of operating procedures and user training	Mid-2024–2025; implemented / ongoing	Operator training completion rate and operational discipline audit scores.	Improved procedural consistency and shift-handover practices.
Accumulation of off-spec volumes in D-9606	Capacity bottlenecks forced long-term storage in tank D-9606, requiring off-site disposal.	High (red)	Improved operational control and process sequencing	Mid-2024–2025; implemented	Total tonnage of oily wastewater sent to external treatment (t/year) .	External treatment mass reduced in 2025 by 24.2% (Cracker 1) and 4.4% (Cracker 2).
Overfilling risk / lack of monitoring	Insufficient surge tank level surveillance and missing operational threshold alarms.	Medium (amber)	Reinforced surveillance and tank alarms (D-9401/9601/9606/9607)	Mid-2024–2025; implemented	Alarm response time and tank high-level excursion frequency.	Zero tank overfill incidents; increased overall operational flexibility.

4.3. Operational and economic outcomes

A clear metric of the operational relevance of the OILY plant is the mass of oily water requiring external (off-site) treatment and its associated cost. Table 4 reports the tonnage sent to external treatment for Cracker 1 and Cracker 2 over the last three years. In 2025, after implementation of the main low-cost operational and control measures, the mass of oily water sent to external treatment was 4.4% lower for Cracker 2 and 24.2% lower for Cracker 1 than in 2024, with an associated realized saving of approximately USD 3,588.

Table 4. Oily water sent to external treatment over the last three years.

Year	Cracker 2 to external treatment (t)	Cracker 1 to external treatment (t)
2023	164	153
2024	159	161
2025	152	122

The impact was larger in Cracker 1, where most of the collection pits hold effluent that meets the OILY inlet specification and can therefore be fully diverted to internal treatment. In Cracker 2, a fraction of the effluent contains higher hydrocarbon concentrations and unsuitable products (caustic, solvesso) and must continue to be managed externally. Off-site treatment is provided by a licensed regional hazardous-waste manager at an approximate cost of USD 78 per ton, which reinforces the value of maximizing internal treatment whenever technically feasible. Once the coalescing media are replaced and the plant operates at its full rate of 25 m^3/h per train, an estimated saving of nearly USD 21,100 per year is expected.

A consistent normalization of externally treated wastewater by annual production, total wastewater generation, or equivalent operating hours could not be performed because these variables were not available on a comparable basis for the complete study period. Consequently, the 24.2% and 4.4% values should be interpreted as changes in absolute annual off-site treatment mass, not as production-normalized treatment-efficiency indicators. Possible year-to-year changes in production level, wastewater generation, plant operating conditions, and influent composition may therefore contribute to the observed differences. In addition, the 2024 annual total partially overlaps the intervention period and should not be interpreted as a pure pre-intervention baseline. This limitation is explicitly retained to avoid attributing the full annual reduction exclusively to the recovery measures.

Once the coalescing media are replaced and both treatment trains are restored to their nominal capacity of 25 m^3/h, the plant would have a theoretical continuous treatment capacity of 438,000 m^3/year. This operating condition is considered the basis for the projected economic benefit. However, the economic saving is not calculated by assuming that the entire theoretical capacity would otherwise require external treatment. The estimate considers the fraction of suitable oily wastewater that can be diverted from off-site treatment to the recovered OILY plant, while also accounting for the downtime associated with filter backwashing when the filters reach their maximum allowable differential pressure (dP), with each backwash taking approximately 4 hours; therefore, the theoretical continuous

capacity should be adjusted to reflect this operational downtime. In addition, not all oily wastewater streams are currently sent to external treatment, as some suitable effluents are recovered and treated internally within the plant. Consequently, the avoided external-treatment volume represents only the portion of wastewater that would otherwise be sent off-site and can effectively be redirected to the recovered OILY plant.

The estimated avoided external-treatment volume of approximately 270 t/year is based on the volumes of oily wastewater treated externally in previous years, as summarized in Table 4. These historical data provide an indication of the potential volume that could be redirected to the recovered OILY plant under restored operating conditions rather than a fixed or guaranteed annual volume. Using an external-treatment cost of approximately USD 78/t, this volume corresponds to a potential gross avoided-disposal cost of approximately USD 21,100/year.

This figure is intentionally reported as a gross screening-level benefit rather than as a net economic saving. A complete incremental-cost dataset was not available for pumping energy, backwash water and energy, steam cleaning, additional maintenance labor, media replacement, and the proposed analyzer/fast-loop upgrade. The structural measures also remain subject to quotation and project evaluation. Therefore, a full cost-benefit, NPV or payback analysis cannot yet be supported. Such an assessment should incorporate the final capital cost of the coalescing media and analyzer solution together with incremental utilities, maintenance, labor, and downtime before the projected USD 21,100/year can be interpreted as a net benefit.

4.4. Hydraulic performance after optimization

The implemented improvement initiatives were associated with a measurable enhancement in the hydraulic performance of the coalescing filters (V-9603/B), as summarized in Figure 6. The comparison uses historian trends and operating records from the pre-intervention period (2023–early 2024) and the post-intervention period (mid-2024–2025). Because the historian export did not preserve a complete cycle-indexed dataset, the analysis is based on representative operating behavior rather than on a predefined statistical sample of individual cycles.

Before the recovery measures, the coalescing filters typically reached the automatic backwash set point after approximately five days of service with an average representative ΔP buildup rate of nearly 0.08 kg/cm² per day. After implementation of the operational and control measures, the representative filter run length increased to approximately twelve days and the ΔP buildup rate decreased to approximately 0.033 kg/cm² per day, corresponding to a reduction of nearly 59%. Expressed only as a continuous-equivalent indicator, the change from 5 to 12 days would imply approximately 73 versus 30 backwash events per year per continuously operated train; this is a derived indicator and not a direct count of historical events.

Differential pressure is affected by hydraulic and influent conditions, as well as by filter condition. The same treatment equipment and nominal flow-control structure were used in both periods, with each secondary/tertiary train limited to 25 m³/h. However, matched cycle-by-cycle distributions of actual flow and temperature, together with continuous suspended-solids and oil-loading measurements, were not available for the full comparison periods. The intervention itself also included feed-quality controls—most notably the Cracker 2 upstream quench-process temperature permissive and reinforced

sampling—which were intended to prevent unsuitable, highly contaminated feed from reaching the filters. Consequently, the observed reduction in ΔP buildup is interpreted as the result of the recovery package as a whole, including improved influent control, and cannot be statistically isolated from all changes in wastewater composition or operating conditions.

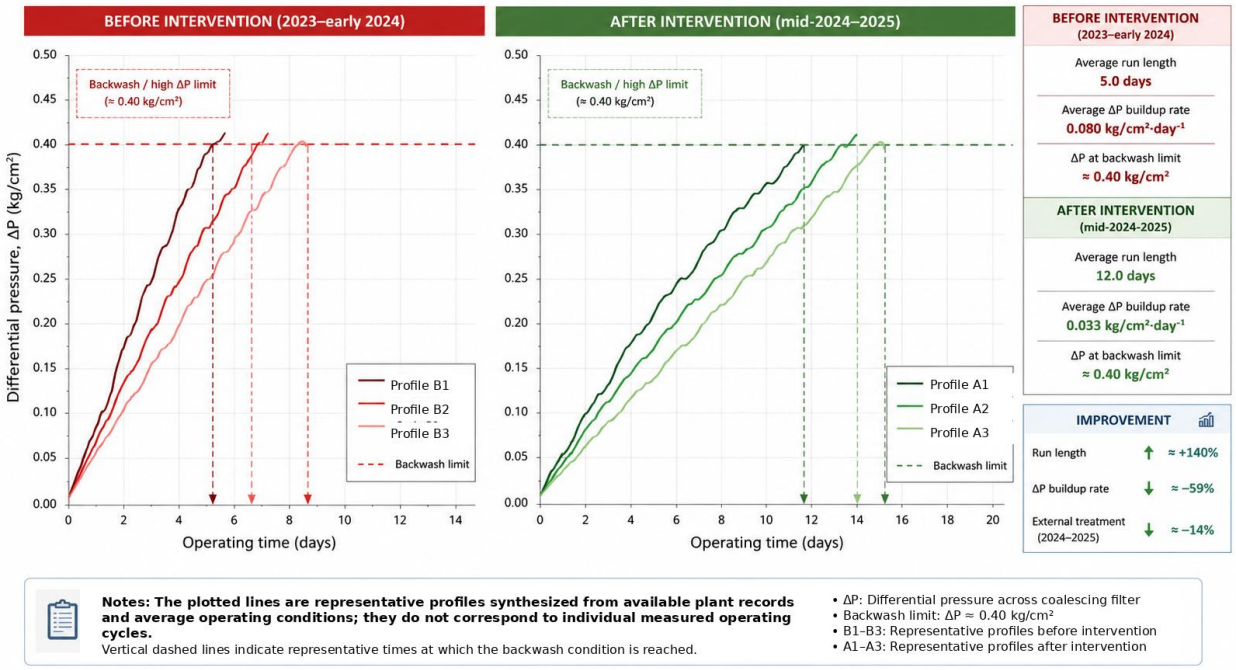


Figure 6. Representative hydraulic behavior of the coalescing filtration system before (2023–early 2024) and after (mid-2024–2025) the operational recovery actions, based on available plant historian trends and operating records. The plotted lines are representative profiles synthesized from the available records and are not individual experimental replicates.

The comparison therefore supports an operational association rather than a controlled causal estimate. The longer representative run length and lower ΔP buildup occurred after the combined implementation of control-logic corrections, feed-quality interlocks, reinforced sampling and monitoring, operating-discipline measures, and maintenance actions. Since these measures were implemented as an integrated recovery program, their individual contributions cannot be separated with the available retrospective data.

The approximately 5-day and 12-day values are therefore representative operating conditions, not fixed cycle durations or sample means calculated from a complete list of individually tagged cycles. An exact cycle count and statistically valid range cannot be reconstructed from the archived historian export. This limitation is now stated explicitly and the figure is presented as a descriptive engineering comparison rather than a statistical demonstration of treatment response.

The lower average fouling rate reduced the frequency of backwashing operations, increasing equipment availability and improving process continuity. The longer operating cycles also reduced the number of operational interventions and allowed a more efficient use of maintenance resources. Overall, these results indicate that controlling influent wastewater quality, together with standardized

operating practices, can improve the performance of coalescing filtration systems in oily wastewater treatment facilities.

5. Discussion

The results show that the loss of efficiency of the plant did not stem from a single cause but from the convergence of operational, mechanical, and organizational factors. Degradation of the V-9603/B filter media, plugging of lines and valves that hindered critical maneuvers (e.g., draining), recurrent TOC-analyzer failures that prevented automatic quality verification, and weak operational discipline (sampling, monitoring of key variables and preventive cleaning) acted together, with control-logic inconsistencies that could trigger overfilling or relief activation.

Several measures (sampling routines, control-code adjustments, hydraulic-alignment verification and procedure updates) produced sustained operational improvement and a measurable reduction of externally treated effluent and its cost. Nevertheless, the outcomes reported here are partly preliminary: the two structural measures with the largest expected impact (media replacement and the TOC-analyzer solution) are still in progress, so the full design throughput and the associated potential saving has not yet been realized. The reductions should therefore be read as the effect of low-cost operational and control measures, with further gains expected once the structural actions are completed.

Three limitations deserve emphasis. First, the COD/TOC correlation is not universal and can become unstable under changing water composition, which constrains the reliability of the on-line surrogate and motivates the analyzer upgrade. Second, the variability of the quench water from Cracker 2 imposes recurrent disturbances on the treatment trains that purely operational measures can mitigate but not eliminate. Third, the physical–mechanical nature of the process (coalescence plus filtration) limits its ability to handle complex dissolved organics; broadening the inlet streams would require additional technologies, such as induced-gas flotation, advanced oxidation, or biological clarification.

The quantitative assessment presented in this study focuses primarily on hydraulic and operational recovery rather than on a complete before-and-after demonstration of chemical treatment efficiency. TOC is monitored online for routing purposes, whereas COD, oil and grease, suspended solids, total hydrocarbons, and BTX rely on laboratory or specific monitoring records. A complete paired pre/post dataset for these parameters was not available for the study periods and therefore removal efficiencies or statistically comparable concentration distributions are not reported. The values listed in Table 1 are operating/discharge specifications, and the BTX figure reported for the gas-stripping stage is a design target rather than a measured intervention outcome. Accordingly, the verified quantitative conclusions are limited to hydraulic behavior, operational continuity, and reduction in off-site treatment, and this absence of comprehensive pre/post water-quality data is recognized as a central limitation of the study.

The Industry 5.0 perspective is used here as an interpretative framework rather than as a methodology that was prospectively operationalized through a dedicated indicator set. Nevertheless, several measured or directly derived outcomes provide quantitative support for the sustainability and resilience dimensions. Sustainability is reflected in the 2025 reduction in oily wastewater sent to external treatment (24.2% for Cracker 1 and 4.4% for Cracker 2 relative to 2024), with a realized avoided-disposal saving of approximately USD 3,588 and consequently lower demand for external transport and treatment. Resilience is supported by the increase in representative filter run length from

approximately 5 to 12 days and the 59% reduction in ΔP buildup rate, which imply greater operating continuity and a lower backwash-intervention frequency. No further V-9602 relief activations associated with the corrected logic were reported in the post-intervention records. Human-centricity remains the least quantitatively measured dimension: operators and technical personnel participated in diagnosis, procedures and training were reinforced, and safer operating/maintenance practices were introduced to reduce exposure during abnormal conditions, but no formal ergonomic, exposure, or workload indicator was collected. Thus, the Industry 5.0 framing is supported most directly by measurable sustainability and resilience outcomes, while the human-centric contribution remains qualitative and complementary. Table 5 summarizes the indicators that can be supported by the available data.

Table 5. Measured or derived indicators supporting the Industry 5.0 interpretation.

Industry 5.0 dimension	Indicator	Observed/derived outcome
Sustainability	Off-site oily wastewater and avoided-disposal cost	2025 vs 2024: −24.2% Cracker 1; −4.4% Cracker 2; realized saving ≈ USD 3,588.
Resilience	Filter run length, ΔP buildup and backwash frequency	Representative run length: 5→12 days; ΔP buildup: −59%; continuous-equivalent backwash frequency: ≈73→30 events/year/train (derived, not a direct count).
Human-centricity	Operator participation, training and safer work practices	Qualitative evidence only; no formal ergonomic, exposure or workload indicator was collected.

6. Conclusions

This study presented a diagnosis-driven recovery program for a full-scale oily wastewater treatment plant operating below its design conditions. Following implementation of the integrated low-cost operational, control, and maintenance package, the representative coalescing-filter run length increased from approximately 5 to 12 days and the differential-pressure buildup rate decreased from approximately 0.08 to 0.033 kg/cm² per day, a reduction of about 59%. In parallel, the mass of oily wastewater sent to external treatment in 2025 was 24.2% lower for Cracker 1 and 4.4% lower for Cracker 2 than in 2024, with an associated realized saving of approximately USD 3,588. Because the study is retrospective and matched pre/post distributions of all hydraulic and influent-quality variables are unavailable, these changes are interpreted as operational outcomes associated with the recovery program rather than as a controlled estimate of the causal contribution of each individual action.

Some of the main structural actions identified during the study, particularly replacement of the coalescing media and improvement of the online TOC monitoring system, remain in progress or under

evaluation. Therefore, full design throughput has not yet been restored. The estimated annual value of approximately USD 21,100 should consequently be interpreted as a projected gross avoided-disposal benefit under restored operating conditions, not as a realized or net economic saving. A complete cost-benefit assessment requires final capital quotations and incremental internal operating and maintenance costs. Future work should also establish prospective cycle-level monitoring and a paired water-quality dataset to enable statistically stronger evaluation of hydraulic and treatment performance.

Use of AI tools declaration

AI tools were used solely for language editing and readability improvement. The scientific content, analysis, and conclusions of this article were developed exclusively by the authors.

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Conflict of interest

The authors declare no conflict of interest.

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