

Article

Operational Criteria and Challenges in Management of Liquid Waste Treatment Facility Based on Chemical–Physical Processes and Membrane Biological Reactor in Thermophilic Conditions: A Case Study

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Abstract

This study investigates the operation and management of an advanced Italian liquid waste treatment platform, focusing on its dual-line configuration and the challenges posed by increasingly heterogeneous waste streams. The main objectives are to (i) characterize the technological and operational features of the system, (ii) evaluate strategies for dealing with variable waste compositions and non-compliant inputs, and (iii) propose governance measures to strengthen cooperation between producers and operators. The methodology integrates the analysis of operational data from 2022 to 2024 (waste volumes, European Waste Catalogue Codes, reagent consumption, sludge production, and energy use) with a critical assessment of acceptance procedures and monitoring protocols. Results show a 10% increase in liquid waste treated over the study period, a growing predominance of complex EWC codes, higher oxygen demand in the thermophilic reactor, and seasonal fluctuations in sludge production. At the same time, the plant achieved stable or improved performance indicators, with specific energy consumption decreasing to 2.08 kWh/kg COD removed in 2024. The study concludes that modular, flexible treatment systems, supported by rigorous waste characterization and real-time decision-making, are essential to ensuring efficiency, regulatory compliance, and long-term environmental sustainability in liquid waste management.

Keywords: liquid waste treatment plant; chemical-physical treatment; thermophilic treatment; advanced management



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1. Introduction

The management and treatment of liquid waste constitute a critical component of modern environmental protection strategies, particularly in industrialized countries like Italy where the pressure on water resources and ecosystems are substantial. As of 2025, the Italian regulatory and operational landscape for liquid waste treatment is shaped by a confluence of increasingly stringent environmental standards, the drive for circular economy

models, and the broader commitments set by the European Green Deal and the National Recovery and Resilience Plan (PNRR) [1]. These developments underscore the need for advanced treatment technologies capable of ensuring high removal efficiencies, process reliability, and sustainable waste valorization pathways [2]. Liquid waste, arising from diverse industrial, agricultural, and civil sources, poses significant challenges due to its variable composition, high pollutant loads, and the presence of substances of emerging concern [3]. Traditional treatment approaches, often based solely on physicochemical processes, may be insufficient to meet current discharge limits or to achieve optimal resource recovery [4]. As such, there is a growing need to integrate multiple treatment stages and to deploy innovative technologies that allow for both flexibility and robustness in waste management systems. In this context, this paper presents a thorough investigation of a state-of-the-art Italian platform for liquid waste treatment, specifically designed to address the multifaceted nature of modern liquid waste streams. The management of platforms for the collection and treatment of liquid waste represents a complex issue that goes much beyond the routine operation of industrial wastewater treatment plants. These facilities have to work at the nexus of technical complexity, regulatory constraints, and often-fragmented stakeholder cooperation. Among the most critical issues confronting such platforms is the intrinsic heterogeneity of the liquid waste they are required to process [5]. Aqueous waste streams can vary significantly not only in terms of chemical and physical characteristics, but also in origin, volume, and potential environmental impact [6]. This variability places considerable demands on treatment technologies and process control systems, requiring a high level of adaptability and specialized knowledge to ensure compliance with environmental standards and operational efficiency. The lack of collaboration between industries (i.e., the waste producers) and operators of treatment facilities is a second equally urgent problem [7]. In the Italian context, this is often compounded by a widespread lack of accountability on the part of waste producers, who may fail to fully acknowledge their role in ensuring that the waste they generate is properly characterized, declared, and pre-treated when necessary. This lack of shared responsibility undermines efforts to standardize procedures and hampers the development of trust-based partnerships, which are essential for the long-term sustainability of the waste management chain [8]. Finally, one of the most delicate operational dilemmas arises when liquid waste loads delivered to the platform do not conform to the qualitative parameters previously agreed upon between the producer and the treatment facility. In these cases, operators must quickly decide whether to accept the non-compliant batch, thus risking negative effects on the treatment process and potential regulatory violations, or reject it, which could have significant logistical and economic consequences. Predictive models for the quality of influents at treatment plants and liquid waste are not widely used and should also be implemented within the management systems of treatment plants [9]. The conflict between technological viability, contractual duties, and environmental responsibility is highlighted by this decision-making process, which is frequently carried out under time constraint and with little information [10]. Together, these three issues—waste heterogeneity, weak producer-operator collaboration, and the management of non-compliant waste streams—form a complex web of challenges that must be addressed through both technological innovation and systemic improvements in governance and accountability within the liquid waste treatment sector. The present study seeks to fill this gap by presenting and critically assessing a cutting-edge Italian liquid waste treatment platform specifically designed to handle highly variable, multi-source waste streams. The novelty of the work lies in its combined focus on technical process adaptability, predictive quality control, and operational strategies for stakeholder cooperation—an approach rarely examined holistically in the national or European context.

Accordingly, the paper pursues three main objectives:

1. Characterize the operational and technological configuration of the selected treatment platform, with emphasis on flexibility and robustness in processing heterogeneous waste.
2. Evaluate the integration of predictive influential quality assessment tools into real-time decision-making for waste acceptance or rejection.
3. Propose a governance-oriented framework aimed at improving cooperation and accountability between producers and operators, thereby enhancing long-term system environmental sustainability.

This work proposes that the proper management of liquid waste is very important for pursuing environmental sustainability. Several aspects are investigated such as the following: (i) the implementation of circular economy principles; (ii) energy efficiency; (iii) the use of advanced treatment technologies (such as MBRs) to reduce environmental impacts; (iv) the reduction of chemical use.

2. Liquid Waste Treatment Plant

2.1. Plant Configuration

The liquid waste treatment plant is structured around two independent, yet complementary, treatment lines, each specifically designed to manage distinct categories and concentrations of incoming waste, as shown in Figure 1. This modular configuration provides flexibility in operational management and ensures optimal allocation of resources based on the nature of the waste streams.

Line 1 is based exclusively on a chemical–physical process. It incorporates conventional operations such as coagulation, flocculation, neutralization, and sedimentation [11]. This line is primarily intended for relatively homogeneous and less complex liquid wastes, where rapid throughput and cost-effective pollutant removal are key priorities. Thanks to its operational simplicity and adaptability, it can handle a broad spectrum of industrial effluents. However, it may present limitations in terms of final effluent quality [12], especially with respect to dissolved organic compounds and emerging micropollutants.

This line is suitable for waste streams that contain the following:

- High concentrations of metals (≥ 100 mg/L);
- Not odorous waste streams;
- Chemical oxygen demand (COD) of 25,000 mg/L.

This treatment line is specifically designed to remove contaminants from wastewater generated by metal production industries through a physicochemical process. Given the nature of these effluents—often containing high concentrations of heavy metals and other substances toxic to biological systems—the treated stream is not subjected to any subsequent biological treatment. Such exposure could impair or even destroy the downstream biomass [13], compromising the overall performance of biological treatment stages within the plant. Line 2 represents a more advanced, hybrid system. It begins with a chemical–physical pre-treatment phase like that of the first line. This initial step serves to protect the subsequent biological treatment from toxic or inhibitory substances and to stabilize the influent composition [14]. Following this, the waste is subjected to a thermophilic biological treatment process, operating at elevated temperatures (typically between 45 and 55 °C), with the use of pure oxygen [15]. From a design perspective, the TAMR system operates with hydraulic retention times (HRT) typically ranging from 6 to 10 days and sludge retention times (SRT) exceeding 150–200 days, ensuring the stable growth of specialized thermophilic microbial consortia. The system employs ultrafiltration (UF) membrane modules, generally in the form of hollow fibers or flat sheets with pore sizes of 0.02–0.1 μm , integrated directly into the aerobic reactor to ensure complete biomass retention and high effluent quality. The mixed liquor suspended solids (MLSS) concentration usually ranges

between 14 and 20 g/L, a condition that promotes low sludge production and enhances the biodegradation of recalcitrant compounds. The integration of a thermophilic membrane bioreactor within a wastewater treatment plant offers promising potential for the removal of emerging pollutants, including pharmaceuticals such as diclofenac, carbamazepine, and sulfamethoxazole, as well as personal care products and endocrine-disrupting compounds like bisphenol A and nonylphenol [13]. This stage is designed to enhance the degradation of organic matter, offering several advantages over conventional biological processes (in mesophilic conditions), including increased reaction rates, low sludge production, and improved pathogen removal efficiency due to the use of pure oxygen in the biological reactor [16]. The TAMR system, an aerobic membrane bioreactor, enables energy recovery through the exothermic heat released during biological degradation, captured via heat exchangers. At the same time, nutrient recovery of carbon and nitrogen is achieved by recirculating ultrafiltration permeate into mesophilic-activated sludge oxidation tanks [13]. To ensure high effluent quality and to manage the biological solids generated during treatment, the second line also integrates a solid–liquid separation step using ultrafiltration membranes. These membranes facilitate the retention of biomass and suspended solids while producing a clarified liquid phase with significantly reduced pollutant concentrations [17]. The integration of chemical–physical and thermophilic–biological processes, along with membrane-based separation technologies, reflects a novel and promising approach to the treatment of complex liquid waste streams [18]. This configuration enables the plant to efficiently handle high-strength or recalcitrant wastes, while also offering opportunities for energy recovery and nutrient recycling [19]. The effluent from the liquid waste treatment plant is mixed with a wastewater stream and subsequently conveyed to a conventional biological treatment process before being discharged into a receiving water body.

This line is suitable for waste streams that contain the following:

- High concentrations of surfactants (≥ 5000 mg/L), typically from detergents and cosmetic formulations;
- High concentrations of nitrates (up to 20,000–30,000 mg/L);
- Odorous waste streams (provided they are free of heavy metals);
- Chemical oxygen demand (COD) higher than 25,000 mg/L.

The following diagram, Table 1, illustrates the decision process for assigning incoming liquid waste to the most suitable treatment line (Line 1 or Line 2).

Table 1. Decision criteria for assigning incoming liquid waste to the most suitable treatment line.

Waste Characteristic	Decision/Allocation
High concentrations of heavy metals (≥ 100 mg/L)	Line 1—chemical–physical treatment only
Odorless waste streams	Line 1—if COD $\leq 25,000$ mg/L
COD up to 25,000 mg/L	Line 1—efficient pollutant removal
High concentrations of surfactants (≥ 5000 mg/L)	Line 2—hybrid chemical–physical + thermophilic MBR
High nitrate concentrations (20,000–30,000 mg/L)	Line 2—hybrid chemical–physical + thermophilic MBR
Odorous waste streams (free of heavy metals)	Line 2—hybrid chemical–physical + thermophilic MBR
Very high COD ($>25,000$ mg/L)	Line 2—advanced thermophilic treatment
Other heterogeneous/variable streams	Real-time allocation based on capacity and regulations

The modular design of the plant enables real-time allocation of incoming waste to the most suitable treatment line, considering waste characteristics, system capacity, and regulatory requirements. Figure 2 presents the distribution of liquid waste volumes treated in 2022, 2023, and 2024 across the two treatment lines (Line 1—chemical–physical process; Line 2—hybrid chemical–physical and thermophilic–biological process). These data highlight a gradual 10% increase in overall waste treated over the three-year period and provide

the basis for assessing how the plant balances loads between treatment lines and adapts its operation to changing input flows.

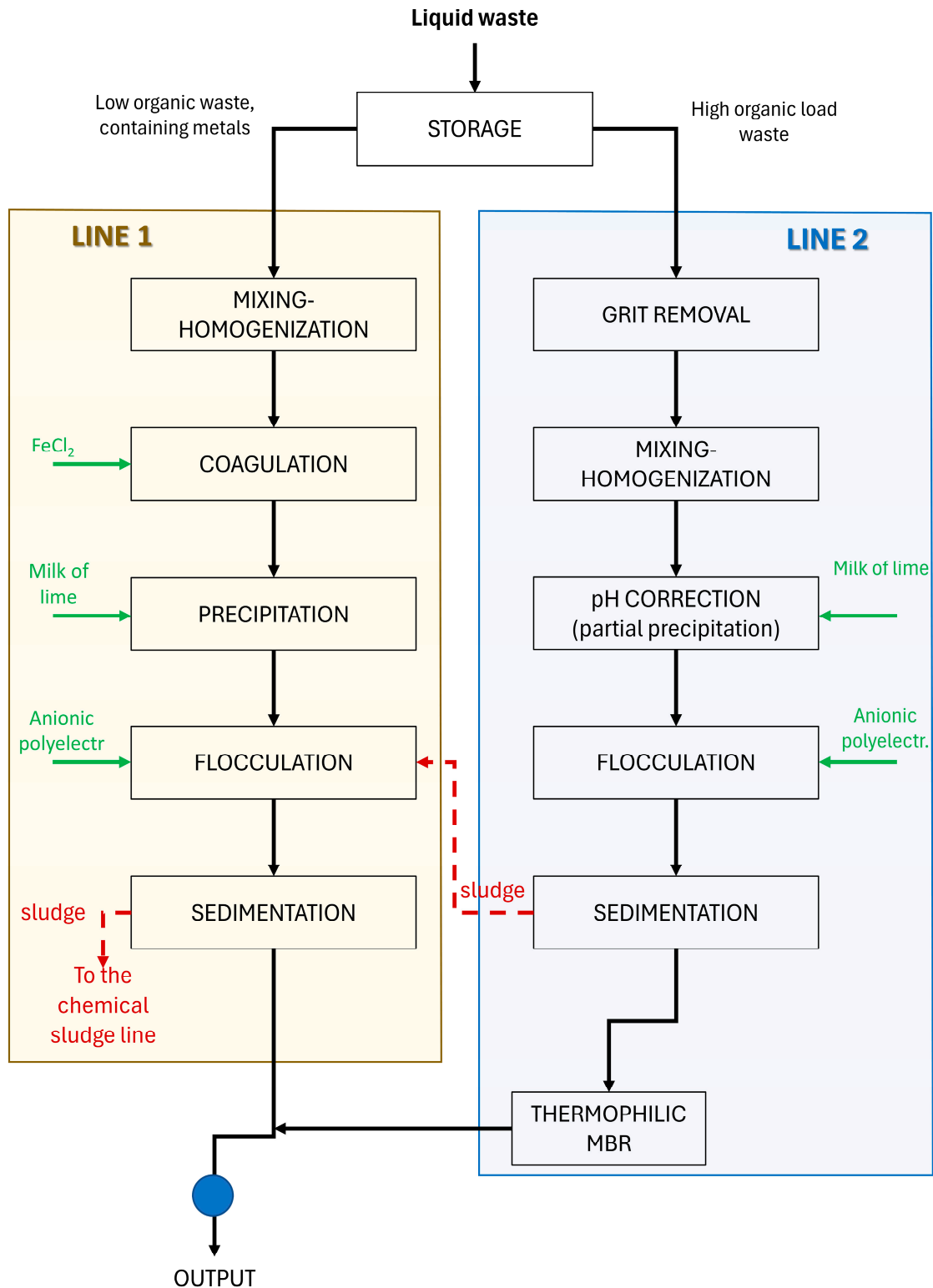


Figure 1. Block diagram of a liquid waste treatment process, showing two parallel treatment lines operating within the overall system.

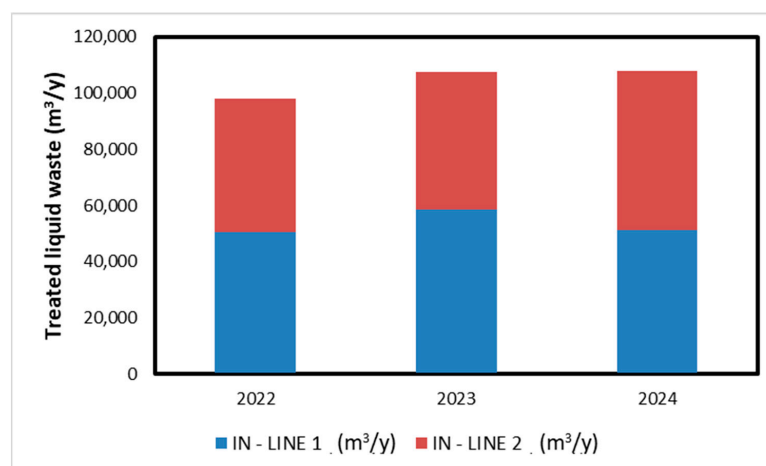


Figure 2. Volume of liquid waste treated by Line 1 and Line 2 (period 2022, 2023, and 2024), (Line 1—chemical–physical process; Line 2—hybrid chemical–physical and thermophilic–biological process).

2.2. Liquid Waste Treated by the Plant

In the European Union, liquid and solid wastes are classified according to the European Waste Catalogue (EWC), also known as the European Waste Code. Within this system, some entries are defined as mirror entries, meaning that the same type of waste can be assigned either a hazardous or a non-hazardous code depending on its specific composition and pollutant content [20]. Each waste stream is assigned a six-digit numerical code that reflects its origin, composition, and hazardous properties. This standardized system is essential for ensuring traceability, regulatory compliance, and proper management of waste across treatment, recovery, and disposal operations. The EWC codes are used by both waste producers and treatment facilities to categorize waste types and to define appropriate handling and treatment procedures.

At the liquid waste treatment plant under study, incoming waste streams are documented and classified using these EWC codes, which offer valuable insight into the variability and complexity of the material received. As illustrated by the comparative analysis of incoming waste for the years 2022, 2023 and 2024 (see Figures 3–5), the composition of the waste entering the plant shows a marked variability from year to year both in quantity and type. The three figures therefore show the percentages of waste treated, highlighting the waste most present for each year.

In 2024, for example, the dominant category was EWC 16 10 02—aqueous liquid waste, other than those mentioned in 16 10 01, which accounted for 23.12% of the total incoming volume. This was followed by EWC 19 02 03—pre-mixed waste consisting only of non-hazardous waste (17.40%) and EWC 07 01 01—aqueous washing liquors and mother liquors (12.01%). Additional significant streams included landfill leachate (EWC 19 07 03, 10.03%) and various other waste from organic chemical processes (e.g., EWC 07 07 01, 8.01%; EWC 07 05 01, 6.26%; EWC 07 06 01, 5.96%).

Although some wastes are consistently represented across multiple years, their relative abundance fluctuates considerably, influenced by external industrial trends, production cycles, and waste generation patterns. Furthermore, specific codes related to hazardous substances (e.g., EWC 19 02 04, EWC 16 10 01, EWC 16 01 14) pose added challenges in terms of treatment compatibility and regulatory oversight.

This heterogeneity confirms one of the central issues discussed in the introduction: the need for a treatment platform that is not only technologically versatile, but also operationally dynamic. Adapting to changing waste profiles requires robust analytical capabilities, flexible process configurations, and real-time decision-making tools that can ensure effective, safe, and compliant waste management practices.

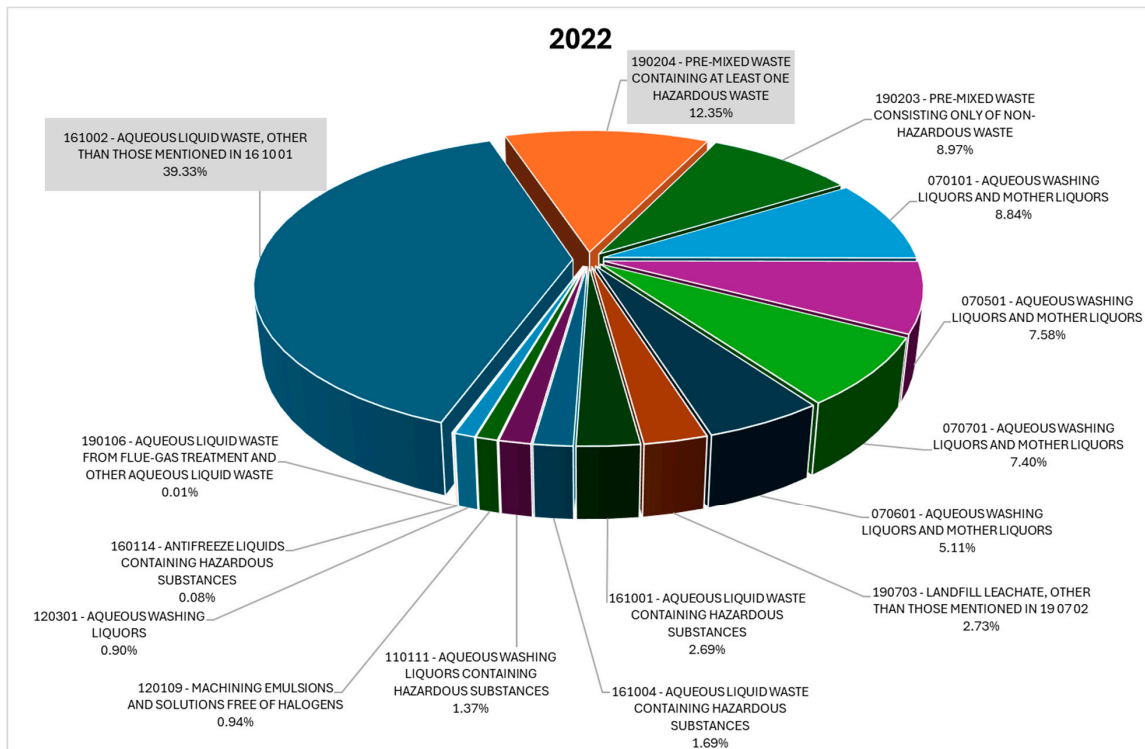


Figure 3. Distribution of liquid waste treated by the plant in 2022, classified according to the European Waste Codes (EWR). The graph highlights the most frequently treated waste types, illustrating the relative contribution of each category to the total annual input. The boxes specify the percentage of treatment for each EWR code treated.

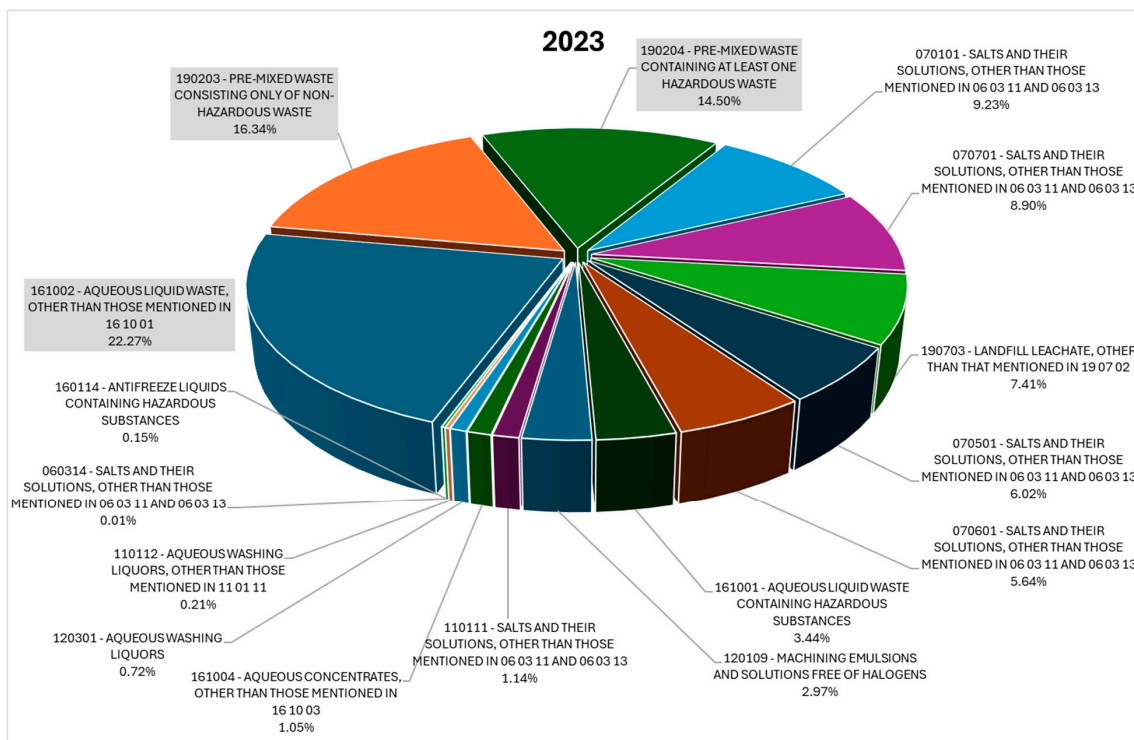


Figure 4. Distribution of liquid waste treated by the facility in 2023, categorized by European Waste Codes (EWC). The chart highlights the most frequently processed waste types, illustrating the relative contribution of each category to the total annual input. The boxes specify the percentage of treatment for each EWR code treated.

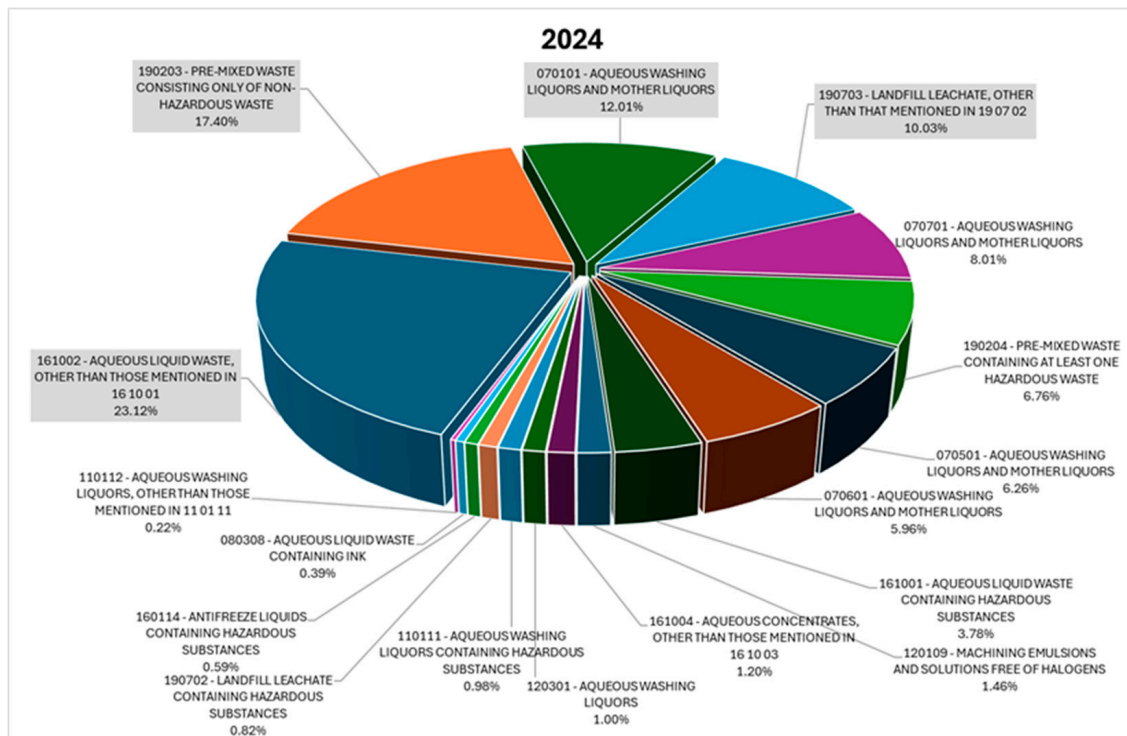


Figure 5. Distribution of liquid waste treated by the facility in 2024, categorized by European Waste Codes (EWC). The chart highlights the most frequently processed waste types, illustrating the relative contribution of each category to the total annual input. The boxes specify the percentage of treatment for each EWR code treated.

2.3. Consumption of Chemicals

The analysis of chemical consumption between 2022 and 2024 was conducted by categorizing reagents into two main groups: those employed in the standard treatment lines (Line 1 and Line 2) and those used in the thermophilic treatment system. As shown in Table 2, total reagent use has steadily increased, with a marked peak in 2024 when consumption exceeded 2 million kg. This surge is primarily linked to the substantial rise in oxygen usage in the thermophilic unit, which alone accounted for over 1.48 million kg. In contrast, reagents dedicated exclusively to Line 1 and Line 2—covering chemical–physical (Chem-Phys) and biological treatments—showed a more gradual growth over the three-year period, averaging nearly 500,000 kg annually. Chem-Phys1 accounted for the vast majority of use (typically 85–100%), with Chem-Phys2 contributing marginally (2–15%) and currently being used only as needed or phased out entirely in some applications. Several reagents are dedicated to specific functions: for instance, conditioning agents for biological sludge dewatering, boosters for nitrifying bacteria (now discontinued), anti-algae products for the cooling tower, and reagents for technical water treatment, such as those used in ion exchange resin regeneration. Additionally, the growing adoption of advanced technologies is evident in the increased frequency of membrane maintenance procedures, including ultrafiltration membrane regeneration and repeated MBR (Membrane Biological Reactor) cleanings. These trends highlight both the evolution of treatment strategies and the rising importance of specialized and energy-intensive processes, particularly in the context of the thermophilic line and high-efficiency separation systems. Some reagents included in the table are not explicitly shown in the routine use shown in Figure 1 due to their occasional use caused by specific treatment needs.

Table 2. Reagent consumption in the plant from 2022 to 2024. The table classifies reagents into two main groups: those used in the standard treatment lines (Line 1 (Chem-Phys1) and Line 2 (Chem-Phys2)) and those dedicated to the thermophilic treatment system. The table also shows the specific consumption of reagents per kg of COD treated and reduced by the plant. In Appendix A, the specific role of each reagent is explained.

Category	Product	2022 [kg]	2023 [kg]	2024 [kg]	Average 2022–2024 [kg]
Plant—Line 1 and 2	Hydrated lime	181,000	255,720	267,740	234,820
	Ferrous chloride	276,560	223,300	252,880	250,913
	Antifoam	2550	1700	2550	2267
	Activated carbon	0	4000	2000	2000
	Cationic polyelectrolyte	3000	4000	2950	3317
	Anionic polyelectrolyte	2000	3000	3750	2917
	Noxa Mix [®]	900	500	0	467
	Micropan (nitrifying bacteria)	0	100	40	47
	Sodium bicarbonate	0	600	400	333
	Hidrofloc CH 685 [®]	0	175	0	58
	Sodium hypochlorite	0	1000	0	333
		Total consumption (excluding thermophilic MBR)	466,010	494,095	532,310
Thermophilic system	Trione tablets	50	0	0	17
	Oxygen	936,240	935,480	1,487,840	1,119,853
	Gemma salt	6100	5000	9000	6700
	Nutrient NUBIL D1 [®]	128,580	58,580	0	62,387
	Nutrient NUBIL D5 [®]	0	0	28,200	9400
	Clanclean [®]	0	0	280	93
	Nitric acid	0	2400	7950	3450
	Caustic soda	1300	1300	7800	3467
	Fosfodnet NA [®]	50	0	150	67
		Total consumption (thermophilic MBR)	1,072,320	1,002,760	1,541,220
TOTAL REAGENTS		1,538,330	1,496,855	2,073,530	1,702,905
Specific consumption					
TOTAL REAGENTS PER COD IN INPUT		0.74	0.82	0.77	0.77
TOTAL REAGENTS PER COD REMOVED [-]		0.77	0.84	0.78	0.80

2.4. Sludge Production

Figure 6 illustrates the monthly chemical sludge production by the liquid waste treatment plant in the years 2022, 2023 and 2024. Chemical sludge refers to the semi-solid by-product generated during the physicochemical treatment of liquid industrial wastes [21], particularly those involving coagulation, flocculation, and neutralization processes. This sludge is composed primarily of precipitated metal hydroxides, organic matter, and other compounds removed from wastewater streams based on the wastes and reagents presented in the previous paragraphs. The data reveal significant fluctuations in sludge production over the three-year period, with significant peaks in October 2023 (approximately 190 t/month) and January 2023 (approximately 158 t/month), suggesting seasonal variability in waste input or operational changes in treatment protocols. Liquid waste treatment in

terms of COD loading was 2,073,060.33 kg COD in 2022, 1,947,053.12 kg COD in 2023, and 2,320,678.00 kg COD in 2024. Relatively consistent trends in 2024 indicate improved process control or changes in waste stream composition through the use of statistical forecasting techniques such as multiple linear regression and time series decomposition techniques to distinguish between trend, noise, and seasonal components, as shown in previous studies [15]. These trends provide valuable insights into the efficiency and environmental impact of the facility's waste management practices.

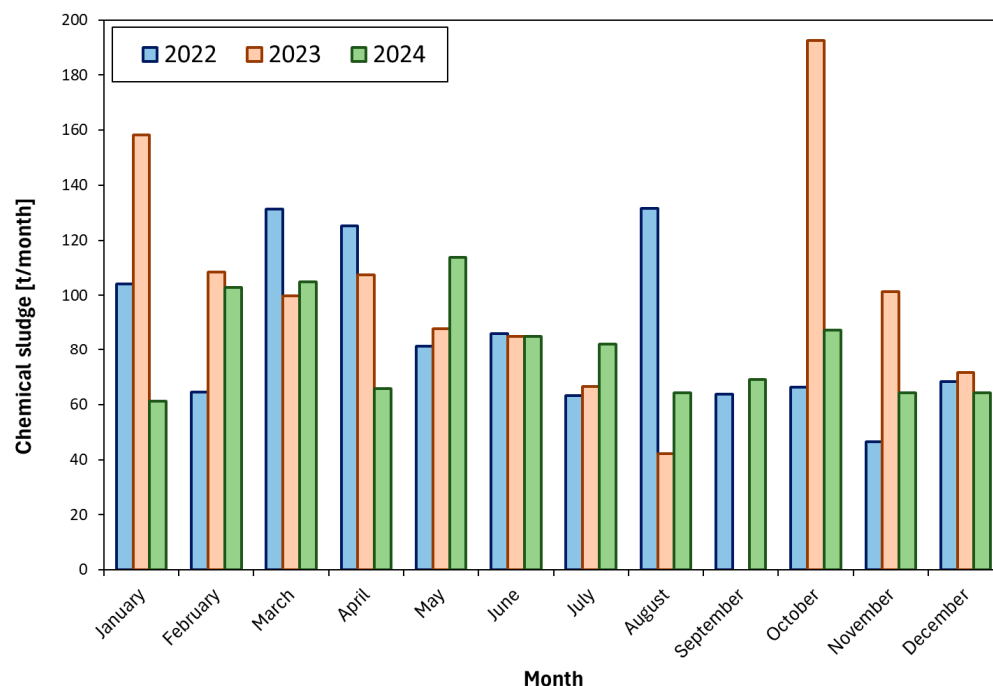


Figure 6. Monthly production of chemical sludge at a liquid waste treatment plant for the years 2022, 2023, and 2024. Chemical sludge refers to the solid residues generated from the physicochemical treatment of industrial wastewater, including coagulation, flocculation, and precipitation processes.

2.5. Energy Consumption

Figure 7 shows the plant's specific energy consumption, expressed in kWh per kilogram of COD removed. In 2022 and 2023, values remained relatively constant, hovering around 2.2 kWh/kg of COD removed, indicating stable energy efficiency under comparable operating conditions. In 2024, however, a significant reduction was observed, with specific energy consumption declining to approximately 2.08 kWh/kg of COD removed. This trend suggests an improvement in the plant's overall efficiency, likely related to the optimization of operating parameters and a more effective use of treatment capacity through the application of statistical optimization techniques [15].

In terms of energy balance, the main energy-demanding devices are the aeration system (fine-bubble diffusers and pure oxygen injection), which accounts for 15–25% of total electricity consumption, followed by pumps for recirculation and sludge handling (10–25%), and membrane filtration units (50–65%) due to the need for continuous suction and periodic backwashing. Ancillary systems, including mixers, monitoring equipment, and heat exchangers for thermal management, represent the remaining 10–15%. With respect to the two treatment lines, preliminary monitoring indicates that the thermophilic aerobic membrane reactor (TAMR) absorbs the majority of energy input (around 60–65%), mainly due to oxygen supply and membrane operation. This distribution highlights the importance of optimizing aeration efficiency and membrane operation strategies to further reduce the plant's specific energy demand.

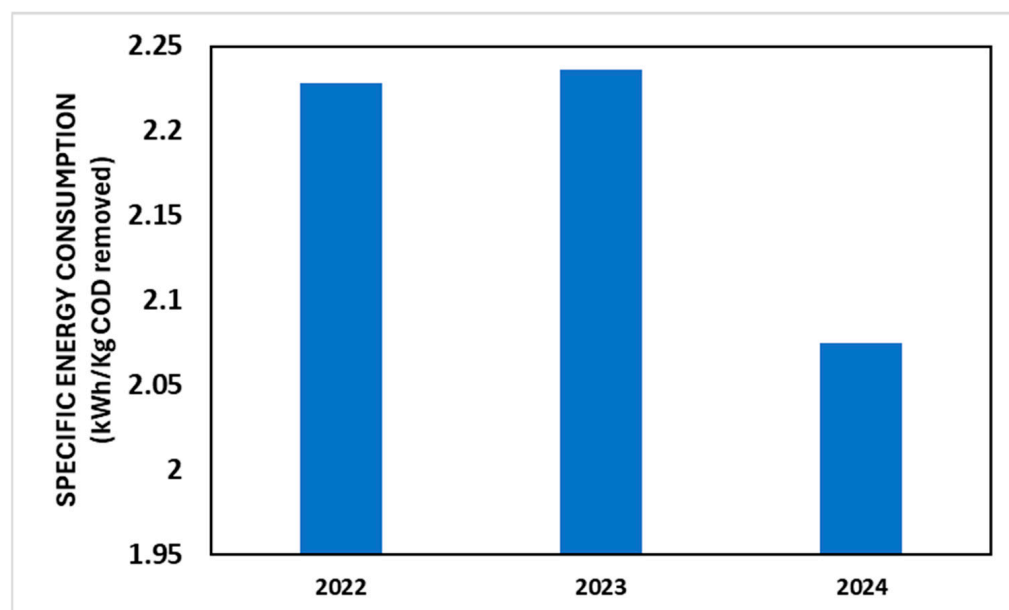


Figure 7. Specific energy consumption of the plant, expressed as kWh per kg of COD removed, for the years 2022–2024.

3. Characterization and Control of Incoming Liquid Waste at the Treatment Facility

The acceptance and management of liquid waste at the treatment facility are governed by strict procedural and regulatory frameworks to ensure both operational efficiency and environmental compliance. Accepted waste categories, according to the European Waste Catalogue, are limited to those specified in the facility's Integrated Environmental Authorization [22]. The admissible quantities are determined in accordance with the limits set by the operating permit, and the facility reserves the right to impose specific quantitative restrictions on individual waste suppliers.

3.1. Acceptance and Homologation Procedures

The acceptance of liquid waste is contingent upon a thorough homologation process, which begins with the submission of a representative 1 L sample for each new waste stream. This sample must be accompanied by a "Waste Descriptive Sheet" drawn up by the producer or intermediary and a valid analysis certificate; the required sheet is shown as Appendix B at the end of the manuscript. In line with the Commission Implementing Decision (EU) 2018/1147 and the associated guidelines for applying the Best Available Techniques (BAT) for waste treatment under Directive 2010/75/EU (notified as C (2018) 5070), the homologation process applied during the acceptance phase at the liquid waste treatment plant is fully compliant with these regulatory instruments. In particular, the acceptance protocol ensures that all operations adhere to state-of-the-art technological practices aimed at minimizing environmental impact while optimizing process efficiency. This rigorous evaluation and approval procedure verifies that the facility's practices are in strict accordance with both BAT conclusions [23] and the Integrated Environmental Authorization (I.E.A.) requirements. Each sample is assigned a unique identification code and recorded in a dedicated register, which is reset annually.

A detailed verification of the EWC code is carried out to confirm that the waste is authorized under the regional or provincial permit. Laboratory simulations of the clarification–flocculation process, replicating full-scale treatment, are then performed. Additionally, respirometric tests (like AUR—Ammonia Uptake Rate, in order to evaluate a

possible inhibitory effect given by high concentrations of ammonia at the exit from the treatment) are conducted on the supernatant to evaluate biological treatability and detect any potential inhibitory effects on the biomass in the biological section of the plant [24].

These laboratory tests are complemented by a comprehensive analytical screening of key pollutants before and after treatment, including chemical oxygen demand (COD), ammonium (NH_4^+), total nitrogen (TN), pH, color, odor, chlorides, and heavy metals. The analytical determinations are carried out following standardized laboratory protocols, such as APHA Standard Methods for the Examination of Water and Wastewater and ISO/EN reference methods, to ensure accuracy, reproducibility, and compliance with regulatory requirements. For example, COD is typically measured using the dichromate reflux method (ISO 6060 [25] or APHA 5220D[26]), ammonium by spectrophotometric analysis with Nessler reagent or ion-selective electrode methods (ISO 7150-1 [27]), and total nitrogen by persulfate digestion followed by UV spectrophotometry (APHA 4500-N). Heavy metals are quantified through inductively coupled plasma–optical emission spectrometry (ICP-OES, ISO 11885 [28]) or inductively coupled plasma–mass spectrometry (ICP-MS, ISO 17294-2 [29]), while chlorides are analyzed via titrimetric (Mohr method, ISO 9297 [30]) or ion chromatography. Physical parameters such as pH, color, and odor are determined using pH-meters, spectrophotometric assays, and organoleptic assessments according to standardized guidelines.

3.2. Ongoing Waste Characterization and Monitoring

Once a waste stream has been accepted, ongoing deliveries are subject to continuous monitoring and periodic recharacterization. A new 1 L sample is taken directly from the transport vehicle on the first delivery following the expiration of the previous analytical report. This ensures the integrity and traceability of the waste profile over time.

For each delivery, an instantaneous sample is analyzed to verify key operational parameters. The standard frequencies for each monitored parameter are outlined in Table 3. The facility may increase sampling frequencies for specific parameters based on the waste type and variability of the incoming stream. In cases involving mirror entries in the EWC, further assessments are conducted to determine whether the waste is classified as hazardous or non-hazardous.

Table 3. Monitoring parameters and frequencies for incoming liquid waste.

Parameter	Frequency
pH	Every delivery
Temperature	Every delivery
color	Every delivery
odor	Every delivery
Electrical conductivity at 20 °C	Every delivery
Settleable solids (2 h)	Semiannual
Suspended solids (TSS)	Semiannual
Chemical Oxygen Demand (COD)	Every delivery
Biochemical Oxygen Demand (BOD ₅)	Semiannual
Ammonium (NH_4^+)	Every delivery
Metals: Al, As, B, Ba, Cd, Cr total, Cu, Fe, Mn, Ni, Pb, Sn, Zn	Every delivery
Metals: Cr(VI), Hg, Se	Semiannual
Nitrates	Semiannual
Nitrites	Semiannual
Total nitrogen (TN)	Weekly
Total phosphorus (TP)	Every delivery
Organotin compounds	Semiannual

Table 3. *Cont.*

Parameter	Frequency
Total cyanides	Semiannual
Sulfides	Semiannual
Sulfates	Semiannual
Sulfites	Semiannual
Chlorides	Every delivery
Fluorides	Semiannual
Anionic surfactants (MBAS)	Semiannual
Non-ionic surfactants (TAS)	Semiannual
Animal/vegetable oils and fats	Semiannual
Total hydrocarbons	Semiannual
Phenols	Semiannual
Aromatic organic solvents	Semiannual
Chlorinated organic solvents	Semiannual
Nitrogen organic solvents	Semiannual
Phosphoric pesticides	Semiannual
Chlorinated pesticides	Semiannual
Other solvents	Semiannual
Hazard class characterization	Semiannual
Respirometric tractability test	At homologation and upon anomaly

This structured approach to waste characterization and control ensures safe, effective, and environmentally compliant operation of the treatment facility [31].

4. Storage of Liquid Waste at the Treatment Facility

4.1. Scheduling of Deliveries

Waste delivery scheduling is managed on a weekly basis through the use of a dedicated management software. Preceding the week of the intended delivery the Plant Manager uses a dedicated software system to draft the weekly delivery schedule, considering the following:

1. Contract acceptance and payment of any required deposit;
2. Compliance with discharge limits and the operational status of the treatment system;
3. Pollutant load and mutual compatibility among waste streams;
4. Maximum allowable storage and treatment capacities;
5. Designated treatment line for each waste input.

Once approved by management, the confirmation or denial of the delivery request is communicated to the client via email.

4.2. Delivery and Controls

Upon arrival, facility personnel receive the required documentation from the transporter and perform several verifications:

1. Verification of the Waste Identification Form (FIR) to ensure alignment with contractual details (EWC code, origin) [32];
2. Confirmation that the delivery is listed in the daily schedule. Unscheduled deliveries are assessed for exceptional approval by the Plant Manager;
3. Compliance with ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road) regulations, including inspection of vehicle certifications and driver qualifications [27].

Only after successful completion of all checks does the waste proceed to weighing and sampling. A sample is collected from the upper layer of the tank using a sampling rod, ensuring a stratified representation of the waste [28]. During this process, a visual inspection is conducted to identify anomalies such as surface oil, foaming, or intense odors, which are reported to the laboratory as necessary [29].

A minimum set of analytical tests is conducted to verify that the delivered waste is consistent with the sample approved during the initial characterization (homologation). These tests align with the facility's standard monitoring parameters. All results are logged into management software either on the same day or the following day.

Samples are stored in a designated laboratory area for three days of post-delivery. Every six months, a 1 L sample is collected from the delivery vehicle and sent to an accredited external laboratory for full-spectrum analysis. This procedure is dictated by the official sampling date on the analytical certificate [30]. Based on these outcomes, the facility may adjust the monitoring plan to include specific contaminants relevant to waste type, in accordance with the current I.E.A.

Only upon full compliance with the required checks is authorization granted for discharge into the appropriate storage tank. If the waste is deemed non-compliant, the client is informed, and a formal notification is issued to the regulatory authorities within 24 h, in line with legal requirements.

4.3. Discharge into Storage Tanks

Once laboratory approval is obtained, plant operators initiate the unloading of waste into the designated tank or storage basin, as determined by the Plant Manager. Tank selection is based on the following:

- Weekly intake scheduling;
- Distribution between different clarification–flocculation treatment lines (CF I and CF II);
- Pollutant load: storage tanks are classified by the hydraulic loading rate into slow, medium, or fast feed rates.

Facility staff instruct the driver on where to position the vehicle for unloading and record all relevant data (selected tank/basin, discharged volume, any residual quantity, names of attending operators) in management software. The driver, under supervision, connects the vehicle's outlet to the facility's unloading system and opens all necessary valves. After confirming readiness, the operator opens the intake valves and activates the pump. Once unloading is complete, the pump is stopped, and the driver is instructed to disconnect the equipment. For ADR-regulated waste, the operator verifies the correct display of orange hazard panels and labels, ensures that inspection ports and valves are sealed, and removes any hazardous residues around the connection point [31]. The vehicle then returns to the weighing station for final weighing, and the Waste Identification Form is completed with the actual discharged volume.

5. Criterion for Waste Management and Treatment

Upon arrival, each waste stream is subjected to a preliminary characterization aimed at determining its most appropriate treatment route. The selection criterion is based primarily on the chemical composition of the waste, with particular attention to the concentrations of surfactants, nitrates, heavy metals, odorous compounds, and COD. This process does not involve a strict categorization of waste types, but rather a dynamic assessment that guides both the assignment to Treatment Line 1 or 2 and the feeding rate to the chosen line. For instance, waste streams with high concentrations of heavy metals are directed to Line 1, where a more aggressive chemical process is applied, while metal-free effluents

with elevated COD, surfactants, or nitrates are routed to Line 2, which integrates a milder physicochemical treatment followed by thermophilic biological oxidation. The degree of contamination also influences how gradually or intensively the waste is introduced into the system. As reported in Section 2.1, two distinct treatment lines are in place, each specifically tailored to process waste with different characteristics:

The selection between Treatment Line 1 and Treatment Line 2 is based on the chemical composition of the incoming waste stream. Line 1 is designated for liquid waste with high concentrations of heavy metals, which are incompatible with the CF2 process. These streams undergo a more aggressive physicochemical treatment (CF1), involving initial acidification, addition of ferrous chloride, lime milk dosing to increase pH to 11–11.5, and final flocculation with an anionic polyelectrolyte.

In contrast, Line 2 is reserved for metal-free waste streams that present other complex characteristics, such as very high concentrations of surfactants (≥ 5000 mg/L), elevated nitrate levels (up to 20,000–30,000 mg/L), strong odors, and exceptionally high COD values (typically $> 25,000$ mg/L). These effluents are treated through a milder physicochemical process (CF2), which includes pH adjustment to around 9 and the addition of an anionic polymer to aid flocculation. This is followed by a thermophilic aerobic biological stage using pure oxygen, which enhances microbial activity and accelerates the breakdown of organic matter, ensuring effective treatment of high-COD waste.

After completion of their respective treatments, both waste streams are conveyed to a common mixing point, where they are combined prior to being treated in the conventional biological lines mixed with a wastewater stream. These checks are performed by the competent regulatory authority and are carried out in accordance with the parameters established by the Integrated Environmental Authorization (IEA) [32].

6. Conclusions

The case study demonstrates that modular and integrated treatment approaches are effective in addressing the heterogeneity and complexity of liquid waste streams. The dual-line configuration, combining chemical–physical processes with thermophilic MBR technology, ensured high adaptability and compliance with environmental standards. Operational data confirmed an overall 10% increase in waste treated from 2022 to 2024, accompanied by stable reagent consumption ratios per COD removed and a significant reduction in specific energy use (from 2.2 to 2.08 kWh/kg COD removed). Sludge production trends reflected both seasonal fluctuations and improved process control in 2024. These findings highlight the facility's ability to maintain high performance despite variable input conditions, while also demonstrating the growing importance of resource-intensive but efficient processes such as thermophilic–biological treatment. Beyond the technical aspects, the study emphasizes the need for strengthened governance, enhanced collaboration between waste producers and operators, and wider adoption of Best Available Technologies (BAT) to ensure both operational efficiency and alignment with circular economy principles. Innovative technologies and practices will continue to develop, along with robust cooperation among stakeholders. These advancements will assist industries in minimizing their ecological footprint and improving the efficiency of industrial liquid waste management.

7. Innovation, Comparison, and Future Prospects

The innovation of this work lies in the evaluation of a large-scale Italian liquid waste treatment platform that combines chemical–physical processes with thermophilic MBR technology, while integrating governance aspects such as waste acceptance protocols and producer–operator cooperation. Compared to similar plants in the European Union, the studied plant demonstrates competitive performance particularly in terms of COD removal

efficiency and specific energy consumption, which in 2024 decreased to 2.08 kWh/kg of COD removed, values in line with or lower than those reported for other advanced biological systems at a European scale. At the same time, the modular, dual-line configuration offers a level of flexibility rarely documented in comparable case studies. Future work should focus on further optimizing reagent consumption, developing strategies to minimize sludge generation, and integrating predictive modeling tools for waste characterization and process control. Broadening the comparison with other EU plants will also be essential to benchmark performance and identify best practices that can guide both technological development and regulatory frameworks.

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Appendix A. Main Reagents Used in the Liquid Waste Treatment Plant and Their Specific Role in the Process

Table A1. Main chemicals and additives used in Plant Lines 1, 21, and 2, and in the thermophilic system, with their specific functions in water and wastewater treatment processes.

Category/Product	Specific Role
Plant—Line 1 and 2	
Hydrated lime	pH adjustment and precipitation of metal hydroxides.
Ferrous chloride	Coagulant for removal of phosphorus, colloids, and metals.
Antifoam	Foam control in tanks and reactors.
Activated carbon	Adsorption of refractory organics, micropollutants, and odors.
Cationic polyelectrolyte	Flocculant to promote particle aggregation.
Anionic polyelectrolyte	Flocculant, often combined with cationic agents to improve settling.
Noxa Mix [®]	Nutrient/additive blend to enhance biological activity.
Micropan (nitrifying bacteria)	Inoculum of nitrifying bacteria to support nitrogen oxidation.
Sodium bicarbonate	Alkalinity source and pH buffer, essential for nitrification.
Hidrofloc CH 685 [®]	Specific flocculant to improve sludge settling.
Sodium hypochlorite	Oxidant/disinfectant for controlling unwanted microorganisms and odors.
Thermophilic system	
Trione tablets	Biocide for controlling undesirable microbial growth.
Oxygen	Supply of pure oxygen to sustain thermophilic biodegradation.
Gemma salt	Regenerant for ion-exchange units and auxiliary systems.
Nutrient NUBIL D1 [®]	Nutrient supplement (N/P) to balance stoichiometric ratios.
Nutrient NUBIL D5 [®]	Alternative/complementary nutrient source for biological processes.
Clanclean [®]	Cleaning agent for MBR membranes.
Nitric acid	pH control and removal of scaling deposits in membrane systems.
Caustic soda (NaOH)	Neutralization, pH control, and membrane regeneration.
Fosfodnet NA [®]	Phosphorus-based additive to support biomass activity.

Appendix B. Waste Characterization

Table A2. Standardized template for administrative, technical, and logistical data collection regarding waste producers and their waste streams, including classification, origin, quality, handling, and supporting documentation.

Section	Field	Information
A. Administrative/Identification Data	Name of Waste Producer	
	Production Site Address	
	Municipality/Province/ZIP Code	
	Registered Office Address	
	Municipality/Province/ZIP Code	
	Tax Code/VAT No.	
	ATECO Code (2007)	
	IEA Site (Yes/No + IPPC codes)	
	RIR Site (Yes/No)	
	Production Site Activities	
	Is Producer a Waste Management Operator? (Yes/No + Details)	
	Website	
	Waste Management Contact (Name/Phone/Email)	
	Client/Intermediary Contact (Name/Company/Phone/Email)	
B. Technical Data	Waste Coding and Classification	
	EWC Code	
	Additional Description	
	Hazardous Characteristics (HP1–HP15)	
	Major Accident Hazard Regulation Applicable? (Yes/No)	
	Appearance and Chemical–Physical Parameters	
	Color	
	Physical State (Powder/Solid/Viscous/Sludge/Liquid)	
	Odor Characteristics	
	Specific Properties	
C. Waste Origin and Quality Conditions	Waste Generation Mode	
	Origin Production Process	
	Raw and Auxiliary Materials Used	
	Substances Listed in Legislative Decree 152/06 (List/Tick)	
	Presence of PFAS?	
	Presence of Solvents/Metals?	
	On-site Waste Storage Conditions	
D. Logistics	Quantity per Service (m ³ /tons)	
	Requested Collection Frequency	
	Packaging for Transport	
	ADR Regulation Compliance (Yes/No + Details)	

Table A2. Cont.

Section	Field	Information
E. Additional Information	Additional Notes	
F. Attachments	Laboratory Chemical–Physical Analysis	
	Safety Sheets for Raw Materials	
	Safety Sheets for Final Products	
	Other (Specify)	
Declaration	Declarant Name and Role	
	Company	
	Date	
	Signature	

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