

Proposal for a new internal processing approach for secondary product from car body surface treatment at the wastewater neutralization station of the automotive paint shop

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Abstract

The study focuses on evaluating a change in the management of secondary product generated in an automotive paint shop during the application of coatings on vehicle bodies, through its treatment in a newly designed technology integrated into the existing operation of the wastewater neutralization station (NS). The proposed technology allows for the separation of secondary product into filtrate ($1,080 \text{ t}\cdot\text{y}^{-1}$) and sludge ($120 \text{ t}\cdot\text{y}^{-1}$), enabling more efficient and environmentally responsible processing directly at the point of origin. Laboratory tests confirmed the effectiveness of FeCl_3 as a coagulant in the separation process, reducing the chemical oxygen demand (COD) concentration from $177,000 \text{ mg}\cdot\text{L}^{-1}$ in the original secondary product to $92,360 \text{ mg}\cdot\text{L}^{-1}$ in the filtrate and further to $616 \text{ mg}\cdot\text{L}^{-1}$ in the treated wastewater. Compliance with key legislative COD and other pollutant limits was confirmed, as the plant's outlet COD value ($1,200 \text{ mg}\cdot\text{L}^{-1}$) remained within the permitted range despite a 100% increase following the addition of filtrate. The implementation of internal waste treatment has eliminated dependence on external end-of-life facilities, resulting in annual cost savings of €227,943 and a reduction in carbon footprint by $26.6 \text{ t CO}_2\cdot\text{y}^{-1}$, primarily due to decreased reliance on tank truck transport. The integrated technological process comprises pipeline transport, coagulation, neutralization, flocculation, and sludge dewatering. The estimated volume of filtrate, $5.4 \text{ m}^3\cdot\text{d}^{-1}$, is marginal in comparison to the plant's average daily wastewater volume of $1,453 \text{ m}^3\cdot\text{d}^{-1}$. The findings confirm the technology's environmental safety, operational viability, and support for sustainable automotive waste management.

Keywords: automotive paint shop, COD, secondary product, neutralization station, wastewater treatment

Introduction

According to the European Automobile Manufacturers' Association (ACEA¹), waste from car production in the EU increased by 3.8% over an 18-year period, rising from 767,123 tons in 2005 to 795,932 tons in 2023. Waste per vehicle grew by 28.2%, from 67.43 kg to 86.45 kg, reflecting long-term production shifts and external disruptions such as economic crises.

In recent years, the automotive industry in Slovakia has faced growing challenges in industrial waste management. While technological progress and production capacity continue to advance, waste processing lags. As an example, from one Slovak Original Equipment Manufacturer (OEM), the amount of unrecovered waste per vehicle increased from 170 g in 2017 to 12 kg in 2022, indicating a significant decline in environmental efficiency. Simultaneously, the number of companies capable of treating specific waste types has plummeted. Paint sludge processors fell from 4 to 1, washing fluid processors from 3 to 1, and liquid waste handlers from 3 to 1. Most critically, processors of packaging contaminated

with hazardous substances dropped from 4 to 0, leaving no domestic treatment options. Even general waste handlers declined from 4 to 2, with the remaining firms offering only transport abroad, not actual processing. These figures underscore an urgent need to rebuild Slovakia's industrial waste infrastructure and align it with growing sustainability demands in the automotive sector. This situation stems from an unstable regulatory environment and low motivation among waste processors to invest in infrastructure. Given the rising pressure for sustainability from car manufacturers, it is essential to strengthen domestic capacities and implement circular economy principles².

Automobile painting processes produce various types of chemically intensive wastewater from surface treatments like degreasing, activation, passivation, electrophoretic deposition, acid cleaning and alkaline cleaning, resulting in high levels of organics, heavy metals, suspended solids, and low biodegradability³. Zhu⁴ also reported that even after upstream physicochemical steps, automobile painting wastewater still had high COD and poor biodegradability, requiring tailored biological treatment to reach acceptable effluent quality. Automotive paint sludge, a complex waste with about 90% water content, is produced in large quantities worldwide, estimated at 200,000 to 500,000 tons annually, due to the low efficiency of spray painting, where up to half of the paint becomes waste. According to Ruffino⁵, recent research has focused on advanced dewatering methods and recovery strategies, including reuse in coatings, incorporation into construction materials, thermal processes for resource recovery, and biological treatments for detoxification and stabilization. Mohtashami⁶ demonstrated that electro flotation effectively removes 90–97 % of total suspended solids from automotive paint wastewater. Güven⁷ found that adding paint shop wastewater to mainstream wastewater of a bus production factory in a lab-scale SBR (Sequencing Batch Reactor) significantly reduced carbon and nitrogen removal efficiency, inhibited nitrification, and lowered microbial growth rates. According to Salihoglu⁸, automotive manufacturing generates significant hazardous waste, primarily paint sludge from the painting process, classified under EWC (European Waste Catalogue) number 080113. Its composition and disposal depend on paint type, application methods, and chemical additives. Due to high organic content, landfilling is prohibited, with incineration and cement kiln combustion as common disposal routes. Research is ongoing into sludge recycling, composting, and bio gasification, alongside innovations in paint chemistry and application to reduce sludge generation.

This study focused on designing a new technological process to improve the handling of secondary product from car body surface treatment at the wastewater neutralization station (NS) of the automotive paint shop. The material arises as a by-product of the production process; however, due to the need for physico-chemical treatment at the current external end-point facility, it is classified as hazardous waste (EWC 080119). After internal processing using the newly designed process, this material has the potential to lose its waste status (end-of-waste), subject to individual assessment by the competent authority.

This waste is generated during the automotive body coating process in the paint shop and is collected in a storage tank at the Paint Mix Room (PMR) facility. It is a liquid material resulting from the automatic cleaning and flushing of application equipment after the completion of a paint batch. This process is controlled by an automated system that prepares the equipment for the next batch of coating material. The waste is a mixture of the cleaning agent CN 36710 VOC FREE HYDROPURGE (at a concentration of 4%) and residual coating materials used in the paint shop. After flushing, the resulting mixture is transported via pipeline to a storage tank located in the PMR. From there, it is regularly, typically twice a week, removed as waste and sent to a licensed end-of-life waste management facility for final treatment. Due to its specific composition and hazardous properties, this material requires targeted technological processing.

The objective was to replace the existing external end-of-life treatment with an internal processing solution integrated into the wastewater NS at the paint shop of an OEM. The proposed solution involves the integration of a dedicated treatment line comprising a storage tank, three reactors for coagulation, neutralization, and flocculation, a sludge press, a filtrate tank, and a sludge container.

Industrial wastewater entering the NS from paint shop operations includes acidic and alkaline effluents generated during chemical pre-treatment of car bodies, such as degreasing, rinsing, and phosphating, as well as wastewater from cathodic painting (electrochemical application of a basic

anti-corrosion coating), oil emulsions, and water contaminated with paint residues. The NS is a dedicated water treatment unit integrated within the paint shop building. It performs physical and chemical treatment of industrial wastewater, which is subsequently discharged into the plant's sewerage system and mixed with sanitary sewage and other wastewater, primarily from vehicle water testing and washing, originating from other areas of the plant. All wastewater is discharged from the plant via a sewage pumping station (PS) into the public sewerage system, ultimately reaching the city's mechanical-chemical-biological wastewater treatment plant (MCB TP). The paint shop generates wastewater at a rate of $46.9 \text{ m}^3 \cdot \text{h}^{-1}$, which is within the design capacity of the NS, rated at $50 \text{ m}^3 \cdot \text{h}^{-1}$. The NS treats up to $226,500 \text{ m}^3$ of industrial wastewater annually, contributing to a total maximum discharge of $385,000 \text{ m}^3$ per year from the plant⁹, including both pre-treated industrial effluent and sanitary sewage.

This article aims to test and evaluate a novel technology for treating a secondary product generated in an automotive paint shop, designed for integration into an existing wastewater NS, intending to reduce environmental burden, operating costs, and the carbon footprint of the process. The originality of the study lies in the real-world validation of an integrated treatment approach implemented directly in an operating industrial system. The study provides empirically grounded evidence of the technical, economic, and environmental performance of the solution, thereby offering a transferable model for more sustainable wastewater management in automotive manufacturing. The technology was further validated under semi-operational conditions through a pilot-scale test, confirming its applicability beyond laboratory settings.

Experimental part

To evaluate the feasibility of transitioning the disposal method for liquid waste EWC 080119 (aqueous suspensions containing paints or varnishes with organic solvents or other hazardous substances) from external to internal processing, laboratory testing was conducted. The tests were designed to verify two critical parameters: (a) the effective separation of the solid waste component (sludge) from its liquid phase (filtrate), and (b) the determination of COD in the filtrate to assess its environmental compliance.

A 0.5 L laboratory sample of liquid hazardous waste was treated with 1.25 mL of 40% FeCl_3 under continuous stirring to induce coagulation. The pH was adjusted to a value of 8 using $\text{Ca}(\text{OH})_2$.

Following agitation, the solid phase settled at the bottom of the container. The precipitated sediment was then separated by filtration through filter paper, yielding a distinct sludge and a clear filtrate. The COD in the filtrate was determined using the dichromate oxidation method in accordance with STN ISO 6060. This is a standardized procedure for determining COD. The water sample is oxidized by potassium dichromate in a strongly acidic medium at elevated temperature. The amount of dichromate consumed is proportional to the concentration of oxidizable substances in the sample and expresses the level of organic pollution. The theoretical COD concentration in the plant's wastewater sewerage, following dilution with the filtrate, was subsequently calculated using a mass balance approach (Equation 1).

$$P_3 = \frac{V_1 \cdot P_1 + V_2 \cdot P_2}{V_1 + V_2} \quad (\text{mg} \cdot \text{L}^{-1}) \quad (1)$$

V_1 – current daily volume (m^3) of wastewater discharged from the plant

V_2 – estimated daily volume (m^3) of filtrate (liquid component after separation from sludge)

V_3 – resulting daily volume (m^3) of wastewater discharged from the plant after mixing with filtrate

P_1 – COD concentration ($\text{mg} \cdot \text{L}^{-1}$) in the current reference sample of wastewater at the plant outlet (sewage PS)

P_2 – COD concentration ($\text{mg} \cdot \text{L}^{-1}$) in the filtrate

P_3 – COD concentration ($\text{mg} \cdot \text{L}^{-1}$) in the plant's wastewater sewerage after mixing with the filtrate

The concentration limits for hazardous substances in the generated waste sludge, as specified in Annex 5 of Act No. 79/2015 Coll.¹⁰, were assessed through analytical testing of both raw sludge (prior to dewatering) and dewatered sludge (after mechanical water removal).

Based on the measured values, the dewatered waste sludge was reclassified to EWC 080113 (sludges from paint or varnish containing organic solvents or other dangerous substances) in accordance with applicable legislation. The average daily volume of wastewater generated by the entire plant (V_1) is 1,453 m³, while the estimated daily production of filtrate (V_2) is 5.4 m³.

As part of the environmental impact assessment, the annual carbon footprint (in tonnes of CO₂) resulting from the transport of liquid waste EWC 080119 from the paint shop to an external end-of-life facility was calculated. Following the implementation of the revised waste handling method, based on internal processing, the carbon footprint was recalculated, reflecting a 90% annual reduction in transport requirements.

The emission factor for diesel fuel (2.54 kg CO₂·L⁻¹) was determined in accordance with STN EN 16258:2013¹¹, a standardized methodology for calculating and declaring energy consumption and greenhouse gas emissions from transport services. The resulting difference between the calculated values led to an overall reduction in the annual carbon footprint.

The economic efficiency of investing in new technology for the treatment of liquid waste EWC 080119 was evaluated using cost-benefit analysis (CBA). The methodology aimed to quantify the difference in waste recovery costs before and after the investment, calculate the payback period, and estimate cost savings over a five-year horizon. The analysis was based on operational and economic parameters associated with car body production and current waste management practices, as outlined in Table 1. The methodology's limitations included the assumption of stable waste recovery prices and a constant volume of waste generation throughout the review period.

Table 1: Operational and economic parameters for CBA

Abbreviation	Parameter	Unit	Value
VK _{1y}	Number of car bodies produced per year	pcs·y ⁻¹	125,000
MO _{1pcs}	Amount of waste generated per car body	t·kg ⁻¹	0.009
MO _{1ys}	Annual waste generation (current situation)	t·y ⁻¹	1,101
I	Investment cost for new technology	€	224,000
MO _{1yi}	Annual waste generation after investment implementation	t·r ⁻¹	120
NO _{1ts}	Recycling cost per ton of waste (current situation)	€·t ⁻¹	334
NO _{1ti}	Recycling cost per ton of waste after investment implementation	€·t ⁻¹	100
NO _{1ys}	Annual recycling cost (current situation)	€·y ⁻¹	367,943
NP _{1yi}	Annual operating cost of the new technology	€·y ⁻¹	20,000
NO _{1yi}	Annual recycling cost after investment implementation	€·y ⁻¹	120,000

Results and discussion

Comprehensive analytical tests of wastewater were conducted at both the NS outlet and the plant outlet (sewage PS), using a reference sample without added filtrate and a sample with added filtrate. The results of these analyses are presented in Tables 2 and 3 of the Results section. The purpose of the analyses was to assess the impact of the filtrate on compliance with wastewater pollution limit values and to verify adherence to the COD limit value as determined by the mass balance method. The results of laboratory tests on the processing of liquid waste EWC 080119, together with analytical tests of wastewater samples, provided the basis for deciding to shift the handling of this waste from external processing to internal continuous treatment. At the same time, they supported the proposal to incorporate new technology into the existing NS facility to enable this treatment.

In standard liquid waste EWC 080119, the COD concentration was measured at 177,000 mg·L⁻¹, as confirmed by analytical testing. Analysis of the filtrate sample, following separation of the solid sludge component from waste EWC 080119, revealed a COD concentration of 92,360 mg·L⁻¹. Using mass balance equation (Equation 1), the COD concentration at the outlet of the sewage PS, following mixing with sewage wastewater, was calculated to be 616 mg·L⁻¹. This confirmed theoretical compliance with the COD limit of 1,200 mg·L⁻¹ at the plant discharge point.

The effectiveness and suitability of the existing NS technology for pre-treating technology wastewater with added filtrate, along with compliance with pollution limit values at the NS outlet to the site's wastewater sewerage, were evaluated based on sampling and analytical testing of two samples: No. AR-24-KT-032584-01 (collected on 6 September 2024) and No. AR-24-KT-032585-01 (collected on 8 September 2024). The obtained results were averaged and compared with the values of reference sample No. AR-24-KT-030990-01, collected on 25 August 2024, which did not contain the added filtrate. Detailed data are presented in Table 2. The results indicated elevated concentrations of dissolved substances residue (DSR) after annealing at 550°C (868 mg·L⁻¹), fluorides (7.18 mg·L⁻¹), and iron (Fe, 0.59 mg·L⁻¹) compared to the reference sample. Nevertheless, all samples containing filtrate remained within the established limit values.

Table 2: Effluent quality indicators of technology wastewater at the discharge point from the NS before and after adding the filtrate

Indicator	Effluent reference sample without filtrate [mg·L ⁻¹] (Protocol No. AR-24-KT-030990-01, 25.8.2024)	Effluent sample 1 with filtrate [mg·L ⁻¹] (Protocol No. AR-24-KT-032584-01, 6.9.2024)	Effluent reference sample 2 with filtrate [mg·L ⁻¹] (Protocol No. AR-24-KT-032585-01, 8.9.2024)	Average value from samples 1 and 2 [mg·L ⁻¹]	Limit value [mg·L ⁻¹]
Adsorbable organically bound halogens (AOX)	0.05	0.05	0.04	0.05	0.4
Aluminum (Al)	0.43	0.41	0.31	0.36	3
Dissolved substances residue after annealing at 550°C	654	826	910	868	-
Fluorides	5.6	6.82	7.54	7.18	25
Iron (Fe)	0.1	0.59	0.58	0.59	3
Nickel (Ni)	0.02	0.01	0.04	0.03	0.4
Non-polar extractable substances (NEL IS)	0.05	0.31	0.06	0.19	10
pH	7.55	7.4	7.14	7.27	6 – 9
Zinc (Zn)	0.01	0.01	0.01	0.01	0.6

Compliance with pollution limit values in sewerage wastewater at the plant outlet (PS), including COD, was verified based on sampling and analytical testing of sample No. AR-24-KT-032728-01, collected on 9 September 2024 following the addition of filtrate. The obtained results were subsequently compared with the average parameter values of two reference samples No. AR-24-KT-030076-01 (collected on 14 August 2024) and No. AR-24-KT-031755-01 (collected on 25 August 2024), which did not contain the added filtrate. Detailed results for all pollution indicators are presented in Table 3. The sample containing filtrate exhibited elevated concentrations of COD (367 mg·L⁻¹), extractable substances (EL, 7.65 mg·L⁻¹), non-polar extractable substances (NEL, 1.58 mg·L⁻¹), phosphorus (P, 3.2 mg·L⁻¹), and nitrogen (N, 44.5 mg·L⁻¹) relative to the average values of the reference samples.

Nevertheless, all monitored parameters remained well within the established limit values, confirming regulatory compliance with a significant safety margin.

Table 3: Effluent quality indicators for sewerage wastewater at the discharge point (PS) of the plant to the external municipal sewerage before and after adding the filtrate

Indicator	Effluent wastewater reference sample 1 without filtrate [mg·L ⁻¹] (Protocol No. AR-24-KT-030076-01, 14.8.2024)	Effluent wastewater reference sample 2 without filtrate [mg·L ⁻¹] (Protocol No. AR-24-KT-031755-01, 25.8.2024)	Average value from samples 1 and 2 [mg·L ⁻¹]	Effluent wastewater sample with filtrate [mg·L ⁻¹] (Protocol. No. AR-24-KT-032728-01, 9.9.2024)	Limit value [mg·L ⁻¹]
Adsorbable organically bound halogens (AOX)	0.094	0.1	0.097	0.11	0.5
Aluminum (Al)	0.55	0.21	0.38	0.28	3
Anionic surfactants (MBAS – Methylene Blue Active Substances)	1.14	0.49	0.82	0.45	10
Chemical oxygen demand (CHSK _{Cr})	342	275	308.5	367	1,200
Dissolved substances residue after annealing at 550°C	1,122	868	995	1.070	1,800
Extractable substances (EL IS – infrared spectroscopy)	3.83	4.05	3.94	7.65	60
Insoluble substances at 105 °C	64	22	43	68	500
Iron (Fe)	0.54	0.27	0.405	0.49	3
Nickel (Ni)	0.016	0.005	0.011	0.014	0.5
Nitrogen (N total)	26.5	35.5	31	44.5	80
Non-polar extractable substances (NEL IS – infrared spectroscopy)	0.44	1.02	0.73	1.58	10
pH	7.95	7.63	7.79	7.7	6 - 9
Phosphorus (P total)	2	2.7	2.35	3.2	15
Zinc (Zn)	0.22	0.1	0.16	0.16	2

The COD concentration (367 mg·L⁻¹) in the sample containing added filtrate was 40.4% lower than the theoretical value calculated via mass balance equation (616 mg·L⁻¹). This discrepancy highlights the significance of residence time in achieving greater dilution of the filtrate within the sewage stream. These results confirm that the proposed change in the handling of waste liquid EWC 080119 at the existing NS facility, consisting of the addition of separate technology for the treatment and separation of waste into filtrate and sludge, is technologically feasible and environmentally safe.

Next, an operational test of internal waste treatment for liquid waste EWC 080119 was conducted. Samples of the resulting raw and dewatered sludge were collected for analytical testing to determine the concentration limits of hazardous substances in accordance with the legislation¹⁰, to assign the appropriate EWC code, and to establish further handling procedures for the residual sludge.

Table 4 presents a comparison of the analytical results. The most pronounced differences between the raw and dewatered sludge samples were observed in the levels of nitrogen, total organic carbon (TOC), water content, and dry matter, as well as in the concentrations of selected metals and organic compounds.

Compared to the raw sludge, the dewatered sludge exhibited markedly higher levels of nitrogen (14,733 mg·kg⁻¹ vs. 2,713 mg·kg⁻¹) and TOC (44.2% vs. 7.74%), along with increased dry matter content (64.2% vs. 38.4%) and reduced water content (14.3% vs. 60.6%). Among the analyzed metals, the most pronounced differences were observed in iron (Fe: 16,735 mg·kg⁻¹ vs. 54,046 mg·kg⁻¹), aluminum (Al: 3,747 mg·kg⁻¹ vs. 2,074 mg·kg⁻¹), and nickel (Ni: 10.5 mg·kg⁻¹ vs. 2,826 mg·kg⁻¹). Notably, the nickel concentration in both samples remained well below the legislative threshold of 5,000 mg·kg⁻¹. With respect to organic contaminants, the dewatered sludge exhibited elevated levels of polycyclic aromatic hydrocarbons (PAHs: 1.06 mg·kg⁻¹ vs. <0.5 mg·kg⁻¹) and extractable organic halogen compounds (EOHCs: 14.2 mg·kg⁻¹ vs. <5.0 mg·kg⁻¹) compared to the raw sludge.

Table 4: Comparison of analytical results for dewatered and raw sludge (EWC 08 01 13) against regulatory limits for hazardous substances in waste.

Indicator	Unit	Results		Limit value in mg·kg ⁻¹ of dry matter (Annex No. 5 to Act No. 79/2015 Coll.)
		Dewatered sludge (Protocol No. 24/02716)	Raw sludge (Protocol No. 24/02719)	
Zinc (Zn)	mg·kg ⁻¹	38.4	4,391	–
Copper (Cu)	mg·kg ⁻¹	25.8	26.5	–
Nickel (Ni)	mg·kg ⁻¹	10.5	2,826	5,000
Phosphorus (P _{total})	mg·kg ⁻¹	136.0	18,298	–
Nitrogen (N _{total})	mg·kg ⁻¹	14,733	2,713	–
Dry matter (at 105°C)	%	64.2	38.4	–
Chromium (Cr)	mg·kg ⁻¹	7.44	103.5	–
Aluminum (Al)	mg·kg ⁻¹	3,747	2,074	–
Iron (Fe)	mg·kg ⁻¹	16,735	54,046	–
Total organic carbon (TOC)	% by weight	44.2	7.74	–
Water	% by weight	14.3	60.6	–
Polycyclic aromatic hydrocarbons (PAH)	mg·kg ⁻¹	1.1	<0.5	100
Extractable organic halogen compounds (EOHC)	mg·kg ⁻¹	14.2	<5.0	100
Benzene	g·kg ⁻¹	<0.1	<0.1	5,000
Toluene	g·kg ⁻¹	<0.1	<0.1	5,000
Phenol index	mg·kg ⁻¹	3.8	0.9	10,000 (phenols)
Mercury (Hg)	mg·kg ⁻¹	<0.5	<0.5	3,000
Arsenic (As)	mg·kg ⁻¹	<1.0	<1.0	5,000
Lead (Pb)	mg·kg ⁻¹	1.2	9.6	10,000
Cadmium (Cd)	mg·kg ⁻¹	<0.5	<0.5	5,000

Despite these differences, all monitored parameters remained within legislative limits, confirming the environmental safety of the proposed treatment process for liquid waste EWC code 080119. The results also support the suitability of the dewatered sludge EWC 080113 for final recovery at an external

end-of-life facility. Based on the concentrations of key indicators in the dewatered sludge, it was classified under EWC 080113 (sludge from paint or varnish containing organic solvents or other hazardous substances). End-of-life treatment options for waste classified under EWC 080113 include high-temperature incineration, stabilization and solidification, physico-chemical recovery, and co-incineration in cement kilns, as confirmed by Salihoglu⁸.

Following the successful operational test of internal waste treatment for waste classified under EWC 080119, which resulted in its separation into filtrate and sludge (EWC 080113), a new technological process for continuous treatment was proposed for integration into the existing NS facility. A schematic representation of both the current NS process and the newly proposed treatment technology is shown in Figure 1. The filtrate is directed to the existing NS technology for further treatment, while the dewatered sludge is transported to an end-of-life facility for final recovery.

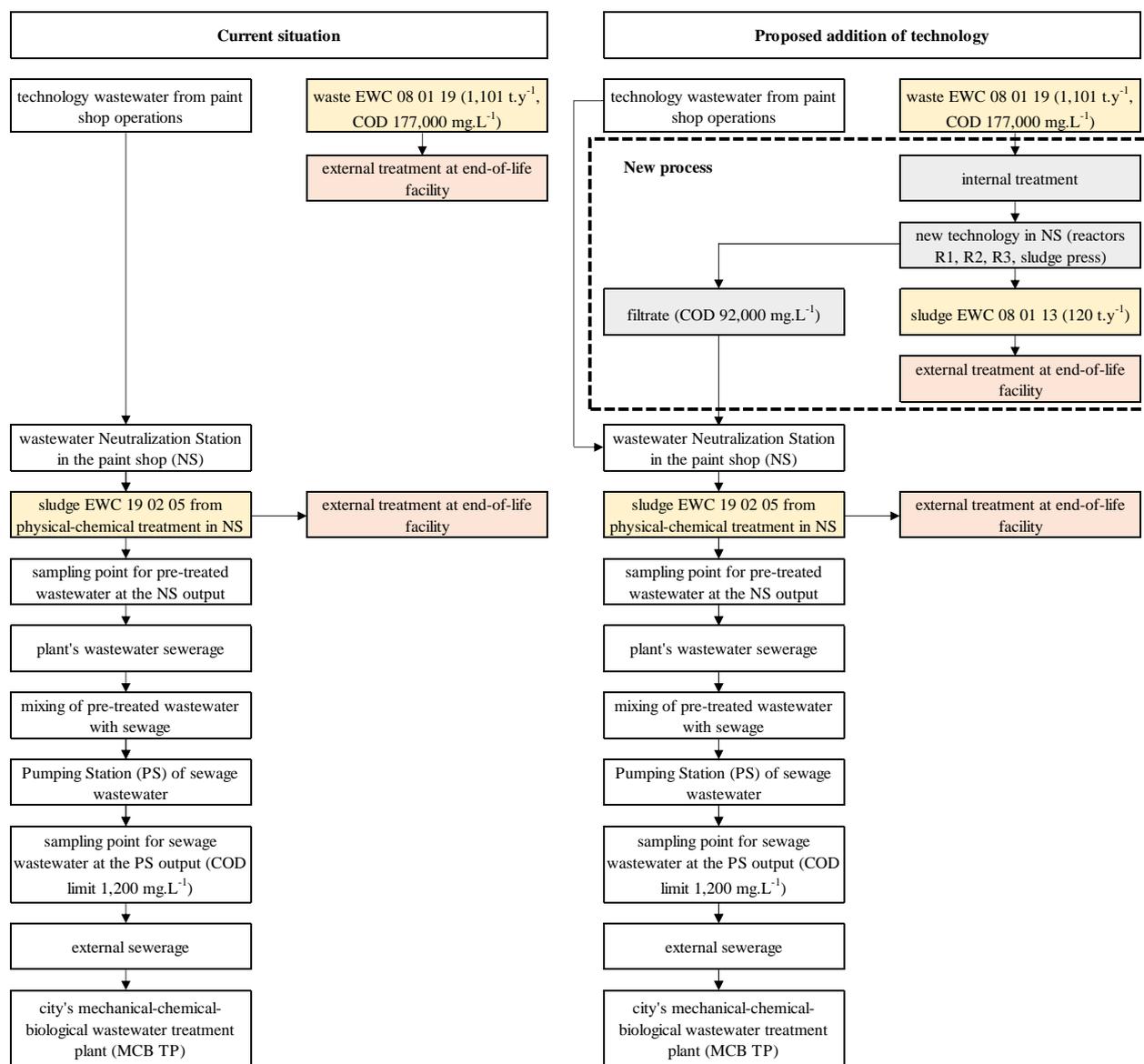


Figure: 1: Scheme of the current and proposed process for treating waste (EWC 080119) at the NS facility

In the first phase of the new process, waste EWC 080119 will be transported via pipeline from the collection tank located in the PMR to the R1 coagulation reactor. An air-operated diaphragm pump will

be connected to the tank, enabling continuous circulation of the material during production downtime and thereby preventing the sedimentation of solid particles.

Following transport, coagulation takes place in reactor R1, where ferric chloride (FeCl_3 , 40%) is applied as a coagulant at a dosing ratio of 1:400. Simultaneously, the pH of the reactor mixture is adjusted to 8 using calcium hydroxide [$\text{Ca}(\text{OH})_2$]. The neutralization process then continues in reactor R2, where calcium hydroxide is added at a concentration of 45%, with continuous stirring to maintain a homogeneous reaction environment.

In the next stage, flocculation occurs in reactor R3 through the addition of a polyelectrolyte-based flocculant and continuous mixing, which facilitates the formation of larger particle aggregates and their subsequent separation. Once the chemical reactions are complete, the treated mixture is transferred via a peristaltic pump to a dewatering unit, a sludge press, where the liquid phase is reduced and separated from the solid sludge.

The sludge is conveyed by gravity into a designated container, while the filtrate is simultaneously drained into a holding tank. From there, it is pumped by a centrifugal pump into the BV 165 neutralization tank for further treatment. The BV 165 neutralization tank is part of the existing NS technology, where the filtrate is treated together with other wastewater streams generated by paint shop operations. This integrated approach enables the efficient incorporation of the processing and treatment of waste classified under EWC 080119 into the main technological system. The entire process will be carried out during the standard three-shift operation in the paint shop, as this type of waste is generated exclusively during manufacturing activities.

To assess the economic efficiency of the proposed solution, a CBA was conducted. The annual car body production (VK_{1y}) is 125,000 units, with an average waste generation per car body ($\text{MO}_{1\text{pcs}}$) of 0.009 tons. This means that the total annual waste production ($\text{MO}_{1\text{ys}}$) amounts to 1,101 tons. Currently, the cost of treatment per ton of waste ($\text{NO}_{1\text{ts}}$) is € 334, which, given the above volume, represents an annual cost ($\text{NO}_{1\text{ys}}$) of € 367,943. The proposed investment (I) amounts to € 224,000, with estimated annual operating costs ($\text{NP}_{1\text{yi}}$) of € 20,000. Following implementation, solid waste sludge ($\text{MO}_{1\text{ri}}$) will continue to be generated at an approximate volume of 120 tons per year. The cost of energy recovery one ton of sludge ($\text{NO}_{1\text{ti}}$) is estimated at € 100, resulting in a reduction of the annual waste recycling cost ($\text{NO}_{1\text{yi}}$) by € 247,943 from the original amount to € 120,000.

The calculation procedure involved determining the new annual costs following the investment, calculated as the sum of the annual waste recovery costs after implementation ($\text{NO}_{1\text{ri}}$) and the operating costs of the new technology ($\text{NP}_{1\text{yi}}$), resulting in a total of € 140,000.

Annual cost savings were calculated as the difference between the original waste management costs ($\text{NO}_{1\text{ys}}$) and the post-investment costs ($\text{NPO}_{1\text{yi}}$), resulting in a total savings of € 227,943. The return on investment (ROI) was calculated as the ratio between the investment amount (I) and the annual cost savings (€ 227,943), resulting in a payback period of approximately 0.98 years. The estimated total savings over a five-year period were determined by multiplying the annual savings by five (€ 227,943 × 5) and subtracting the initial investment, yielding a net benefit of € 915,715.

Based on operational data, the carbon footprint associated with the transport of waste EWC 080119 by a 10 m³ tanker truck was calculated¹¹. Under the original conditions – 104 turns per year and a total distance of 38,896 km, fuel consumption amounted to approximately 11,669 L of diesel, based on an average consumption of 30 liters per 100 km. Using an emission factor¹² of 2.54 kg CO₂ L⁻¹ the total annual transport-related carbon footprint was estimated at 29.6 t CO₂. With the implementation of new internal waste treatment technology, the frequency of waste collection will be reduced by 90%, resulting in a decrease in total distance travelled to 3,890 km, fuel consumption to 1,167 L, and annual emissions to approximately 3 t CO₂, as presented in Table 5.

Table 5: Calculation of carbon footprint reduction

Parameter	Unit	Original state	After project implementation	Reduction
Tank truck turns	turns·y ⁻¹	104.0	10.4	90 %
Distance to end point facility	km·y ⁻¹	38,896.0	3,890.0	90 %
Diesel consumption	L·y ⁻¹	11,668.8	1,166.9	90 %
CO ₂ emissions	t·y ⁻¹	29.6	3.0	90 %

Conclusions

Automotive painting processes generate chemically intensive wastewater and large volumes of paint sludge, both characterized by high organic loads, poor biodegradability, and complex treatment requirements. Recent research highlights the need for advanced separation, recovery, and detoxification technologies to meet environmental standards and reduce the impact of hazardous waste.

The study demonstrated that the proposed technology for the internal treatment of liquid hazardous waste EWC 080119 offers an effective, environmentally sound, and operationally viable solution for implementation within the automotive plant. Separating waste into filtrate and sludge using the proposed new technology will enable further direct processing of the filtrate in the existing NS plant. This will significantly eliminate dependence on external end-of-life facilities, reduce operating costs, and reduce the plant's carbon footprint. Laboratory tests confirmed the effectiveness of FeCl₃ in the separation process, with the resulting concentrations of COD and other pollutants in both sludge and wastewater meeting legislative limits, thereby demonstrating the environmental acceptability of the proposed solution. The marginal proportion of filtrate relative to the total wastewater volume further confirms that integrating the new process into the existing neutralization technology does not pose an operational burden. Overall, the introduction of the proposed technology enhances the sustainability of waste management within the automotive plant and offers a replicable model for similar industrial operations aiming to minimize environmental impacts and optimize waste economy.

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Návrh nového interného postupu spracovania vedľajšieho produktu z povrchovej úpravy karosérie vozidiel na neutralizačnej stanici odpadových vôd automobilovej lakovne

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Abstrakt

Štúdiá sa zameriava na hodnotenie zmeny spôsobu nakladania s vedľajším produktom vznikajúcim v automobilovej lakovni počas aplikácie náterových hmôt na karosérie vozidiel, a to prostredníctvom jeho spracovania v novonavrhnutej technológii integrovanej do existujúcej prevádzky neutralizačnej stanice odpadových vôd (NS). Navrhovaná technológia umožňuje separáciu vedľajšieho produktu na filtrát ($1\,080\text{ t}\cdot\text{rok}^{-1}$) a kal ($120\text{ t}\cdot\text{rok}^{-1}$), čím sa dosahuje efektívnejšie a environmentálne zodpovednejšie spracovanie priamo v mieste vzniku.

Laboratórne testy potvrdili účinnosť chloridu železitého (FeCl_3) ako koagulantu v separačnom procese, pričom koncentrácia chemickej spotreby kyslíka (CHSK) sa znížila z $177\,000\text{ mg}\cdot\text{L}^{-1}$ v pôvodnom vedľajšom produkte na $92\,360\text{ mg}\cdot\text{L}^{-1}$ vo filtráte a následne na $616\text{ mg}\cdot\text{L}^{-1}$ vo vyčistenej odpadovej vode. Súlad s legislatívnymi limitmi pre CHSK a ďalšie znečisťujúce látky bol potvrdený, keďže hodnota na výstupe z prevádzky závodu ($1\,200\text{ mg}\cdot\text{L}^{-1}$) zostala v povolených medziach aj napriek 100% nárastu po pridaní filtrátu v prípade CHSK. Zavedenie procesu interného spracovania vedľajšieho produktu eliminovalo závislosť od externých zariadení na konečné zneškodňovanie, čo viedlo k ročnej úspore nákladov vo výške 227 943 € a k zníženiu uhlíkovej stopy o $26,6\text{ t CO}_2\cdot\text{rok}^{-1}$, predovšetkým v dôsledku obmedzenia prepravy cisternovými vozidlami. Integrovaný technologický proces zahŕňa potrubnú dopravu, koaguláciu, neutralizáciu, flokuláciu a odvodňovanie kalu. Odhadovaný objem filtrátu $5,4\text{ m}^3\cdot\text{deň}^{-1}$ je zanedbateľný v porovnaní s priemerným denným objemom odpadových vôd závodu, ktorý predstavuje $1\,453\text{ m}^3\cdot\text{deň}^{-1}$. Výsledky potvrdili environmentálnu bezpečnosť technológie, jej prevádzkovú realizovateľnosť a prínos pre udržateľné nakladanie s odpadovými medziproduktmi v automobilovom priemysle.

Kľúčové slová: automobilová lakovňa, chemická spotreba kyslíka (CHSK), vedľajší (sekundárny) produkt, neutralizačná stanica, čistenie odpadových vôd