

ENHANCING THE REMOVAL OF SUSPENDED SOLIDS AND PETROLEUM PRODUCTS FROM PIPE-ROLLING WASTEWATER

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Abstract - This paper addresses the treatment of pipe-rolling wastewater, characterized by high concentrations of suspended solids, mill scale, and petroleum products, alongside finely dispersed and colloidal particles. Evaluating current treatment technologies reveals that conventional mechanical sedimentation methods have limited efficiency in removing fine contaminants. This study experimentally investigated the suspended solids settling kinetics under reagent-free conditions and evaluated how chemical treatment enhances the purification process. Findings indicate that applying a ferric chloride-based coagulant combined with an anionic flocculant significantly increases water clarification efficiency (up to 99%). This treatment successfully reduces suspended solids and petroleum product concentrations to 3 mg/L and 1 mg/L, respectively. Furthermore, the study proves that incorporating ballasting agents (microsand, magnetite) promotes the formation of dense flocs and significantly increases settling velocity. These findings justify a two-stage treatment layout comprising mechanical and physicochemical stages. The proposed system ensures compliance with regulatory water quality standards and can enhance the efficiency of closed-loop water recycling systems in metallurgical plants.

Keywords: Wastewater, Pipe-rolling plant, Suspended solids, Mill scale, Petroleum products, Coagulation, Flocculation.

1. Introduction

Modern industrial development, particularly within ferrous metallurgy and the mining sector, drives an increasing anthropogenic impact on the environment. This impact manifests through rising greenhouse gas emissions, intensive water and land resource consumption, and heavy metal accumulation across environmental compartments [1–4]. A paramount environmental challenge involves water pollution from industrial effluents containing high concentrations of suspended solids, metal corrosion products, petroleum products, and various organic compounds [5–7]. Pipe-rolling wastewater demands specific attention. Generated during equipment cooling and hydro-cleaning processes, this effluent exhibits a highly complex dispersed pollutant composition.

Considering strict environmental regulations and the need for sustainable water management, a

critical objective is developing efficient wastewater treatment facilities that enable water reuse within closed-loop recycling systems. This approach not only mitigates the anthropogenic impact on water bodies but also enhances industrial resource efficiency. However, conventional treatment methods applied across many enterprises often fail to achieve the required removal efficiency for fine and colloidal contaminants. Consequently, there is a clear need to upgrade existing technologies and implement intensified treatment processes, particularly through chemical treatment and advanced equipment designs.

This study aims to analyze current approaches to pipe-rolling wastewater treatment, assess their efficiency, and justify pathways for upgrading water purification layouts. To achieve this objective, the following tasks are addressed:

– Analyzing scientific literature on the composition and properties of metallurgical wastewater;

- Investigating existing treatment methods and their efficiencies;
- Determining the primary factors influencing settling processes and pollutant removal;
- Justifying the feasibility of implementing intensified treatment technologies.

Therefore, research in this area is highly relevant, aiming to enhance wastewater treatment efficiency and ensure the environmental safety of industrial operations.

2. Analysis of Literature Data and Problem Statement

Wastewater treatment in ferrous metallurgy, specifically at pipe-rolling plants, remains a critical environmental challenge for modern industry. Highly intensive technological processes generate substantial wastewater volumes containing suspended solids, mill scale, metal corrosion products, alongside petroleum products and other organic contaminants. Recent studies indicate that suspended solid concentrations in these effluents can reach thousands of milligrams per liter (mg/L), significantly complicating the treatment process [8].

The primary contaminants comprise fine and ultrafine iron oxide particles that generate stable colloidal systems. Research indicates that submicron particles (under 1 μm) exhibit a significant zeta potential. This property ensures their aggregative stability and prevents settling under standard conditions [9]. Furthermore, organic substances—specifically petroleum products—adsorb onto mineral particle surfaces. This interaction creates complex dispersed systems that further enhance overall contaminant stability [10]. Conventional treatment methods, such as mechanical sedimentation, are effective only in removing coarse impurities. Typically, the efficiency of these processes does not exceed 70–90%, failing to achieve the necessary removal efficiency for colloidal and dissolved substances [11]. Consequently, modern technologies widely employ chemical treatment methods, specifically coagulation and flocculation. Coagulation reduces colloidal system stability by neutralizing particle charges, whereas flocculation promotes the formation of larger, easily settleable flocs. Utilizing iron or aluminum salts combined with polymeric flocculants ensures high removal efficiency for both mineral and organic pollutants [11]. Studies demonstrate that under optimal conditions, suspended solid concentrations can be reduced to a few mg/L, with petroleum product levels dropping below 1 mg/L [8].

Modern trends in wastewater treatment drive the development of compact and energy-efficient systems that integrate multiple purification stages.

These include lamella clarifiers, flotation units, filtration systems, and combined technologies ensuring high treated water quality and facilitating its reuse within closed-loop recycling systems [12–17].

To intensify settling processes, sedimentation additives or ballasting agents, specifically microsand and magnetite, are increasingly applied. Incorporating these materials promotes the formation of denser and heavier flocs, significantly increasing settling velocity and improving sludge structure [18–20]. This approach proves particularly effective for treating wastewater containing high levels of fine particles and emulsified petroleum products.

Consequently, the literature review demonstrates that effective pipe-rolling wastewater treatment requires a comprehensive approach integrating the mechanical removal of coarse impurities, chemical treatment, and process-intensifying additives. This strategy not only achieves regulatory water quality standards but also ensures the environmental safety and resource efficiency of industrial operations.

3. Research Methodology

The research methodology employs a comprehensive experimental and analytical approach, encompassing field observations, laboratory studies, treatment process modeling, and performance evaluation of technological solutions for pipe-rolling wastewater.

3.1. Object of Study and Wastewater Generation Layout

The object of study was pipe-rolling wastewater generated during equipment hydro-cleaning and cooling processes. The subject of study encompassed pollutant formation dynamics (suspended solids, mill scale, petroleum products) and their subsequent removal via mechanical and physicochemical treatment, including chemically enhanced settling. The facility features a wastewater treatment system (see Fig. 1) comprising four primary clarifiers, four discharge tanks, recirculation pumps, four horizontal clarifiers, and three radial clarifiers.

Equipment washing generates wastewater flow rates of up to 2700 m^3/h , consisting of approximately 2400 m^3/h of recycled water supplemented by fresh water makeup. The contaminated effluent flows into 25-meter-deep primary clarifiers located within the facility. The wastewater generation layout and sampling points are shown in Figures 1 and 2.

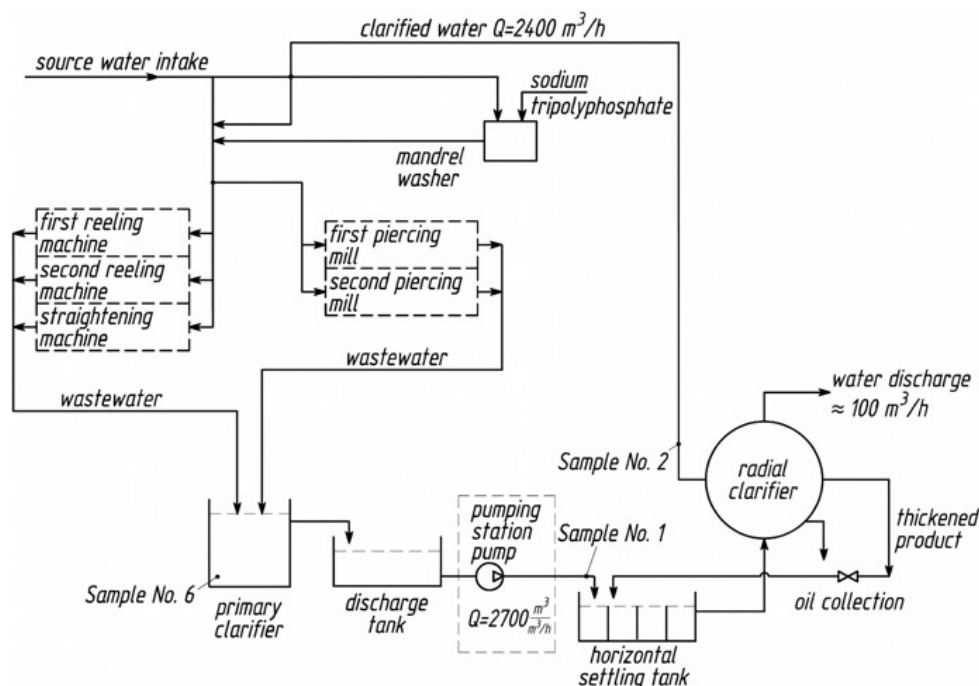


Figure 1: Wastewater treatment system layout at pipe-rolling plant No. 7, indicating sampling points

Coarse and medium-dispersed mill scale settles within the primary clarifiers. The accumulated scale is periodically removed using a grab bucket and sent for remelting. Subsequently, the wastewater flows through underground pipelines into discharge tanks, from where it is pumped into horizontal clarifiers.

Subsequently, the water enters radial clarifiers, where scraper oil skimmers collect the floating oil and a fraction of the fine suspended solids settles.

The thickened sludge from these clarifiers is pumped to the horizontal clarifiers for combined dewatering. The clarified water is then recirculated, though a portion of this recycled stream (~100 m³/h) is discharged into the plant's sewer system. Additionally, the facility utilizes a sodium tripolyphosphate solution at a flow rate of approximately 25 m³/h to wash the rolling mill mandrels.

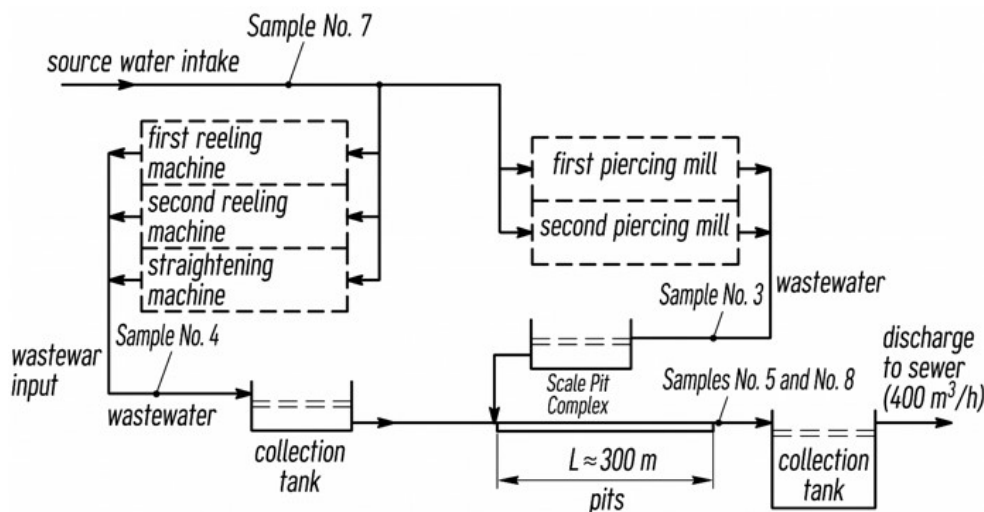


Figure 2: Wastewater generation layout at pipe-rolling plant No. 2

During equipment washing, the water becomes contaminated with mill scale and oil.

The wastewater, at a temperature of approximately 30 °C, flows by gravity into collection tanks and is subsequently discharged untreated into the plant sewer system via underground pipelines (L ≈ 300 m).

3.2. Wastewater Treatment System Sampling

Samples were collected at key points across the treatment layout: at the horizontal clarifier inlets, downstream of the radial clarifiers, following specific technological operations, and at the wastewater discharge point into the sewer.

In total, eight samples were analyzed, encompassing surface runoff, recycled water, and sludge (mill scale). Sampling was conducted over multiple days to ensure a representative assessment of the pollutant composition.

3.3. Laboratory Analysis Methods

Wastewater composition was determined using standard physicochemical methods.

Suspended solid concentrations were measured by drying samples at 105°C to a constant weight.

Mineral and organic fractions were quantified via ignition at 550°C. The organic matter and petroleum product content was calculated as the difference between the dry and ignited residues. The analytical results are presented in Table 1.

To achieve complete suspended solid settling, a coagulant and an anionic flocculant were applied. Following this treatment, the clear supernatant across all samples exhibited residual suspended solid and petroleum product concentrations of up to 3 mg/L and 1 mg/L, respectively.

Table 1. Suspended solids and organic matter concentrations in the wastewater

Sample No.	Suspended solids, m_1 , mg/L	Ignited residue, m_2 , mg/L	Organic residue, $m_3 = m_1 - m_2$, mg/L	Petroleum products, $m_n = m_3 - m_7$, mg/L
1	450	272	178	Not measured
2	226	138	88	Not measured
3	154	136	18	6
4	250	196	54	42
5	192	162	30	18
7	52	40	$m_7 = 12$	0
8	176	136	40	28

Additionally, the ionic composition of the water (Table 2), pH value, and mill scale particle size distribution (Table 3) were determined

Table 2. Wastewater chemical composition (cations and anions)

No.	Parameter	Unit	Concentration
1.	pH	mg/L	7,3
2.	Sodium	mg/L	74
3.	Calcium	mg/L	15
4.	Magnesium	mg/L	18
5.	Potassium	mg/L	5,0
6.	Iron (II)	mg/L	0,01
7.	Iron (III)	mg/L	0,11
8.	Sulfates	mg/L	54
9.	Chlorides	mg/L	49
10.	Bicarbonates	mg/L	201
11.	Carbonates	mg/L	<5
12.	Phosphates	mg/L	7,7

Table 3. Mill scale particle size distribution

Size fraction, μm	Mass fraction, %
+1000	69,71
1000...800	5,79
630...800	5,89
500...630	3,34
300...500	6,04
200...300	4,12
100...200	2,99
63...100	1,47
20...63	0,64
-20	–
Total	100

The analysis revealed that the bulk of the mill scale consists of the coarse fraction ($>1000 \mu\text{m}$); however, a significant portion of the contaminants exists in a finely dispersed and colloidal state.

3.4. Settling Kinetics Study

By design, the particle settling height in the Ecomash 6900 lamella clarifier is 60 mm; therefore, the settling kinetics of suspended solids in the wastewater samples were measured in graduated cylinders at a height of 60 mm.

Prior to the experiment, five 0.12 L portions from the well-mixed Sample No. 4 were poured into five graduated cylinders ($\varnothing 51 \pm 1$ mm), resulting in a liquid column height of 60 mm. During the experiment,

the solids gradually settled, leading to the clarification of the liquid. The amounts of settled and remaining suspended solids were measured at intervals of 20 s, 5 min, 1 h, 2 h, and 3 h. The results are presented in Table 4.

Table 4. Settling kinetics of suspended solids

Settling time	Settled solids, M_1 mg/L, (proportion of total, M_1/m_1 , %)	Ignited settled solids, M_2 mg/L	Organic content in bottom sediment, $M_3 = M_1 - M_2$ mg/L, (organic content in settled solids, M_3/M_1 , %)	Residual suspended solids M_4 mg/L, (proportion of total, M_4/m_1 , %)	Ignited non-settled solids M_5 mg/L	Organic content in non-settled solids, $M_6 = M_4 - M_5$ mg/L, (organic content in non-settled solids, M_6/M_4 , %)
20 s	58 (23,2%)	50	8 (13,8%)	192 (76,8%)	146	46 (23,9%)
5 min	142 (56,8%)	117	25 (17,6%)	108 (43,2%)	79	29 (26,8%)
1 h	192 (76,8%)	159	33 (17,0%)	58 (23,2%)	37	21 (34,5%)
2 h	196 (78,4%)	163	33 (16,8%)	54 (21,6%)	33	21 (38,9%)
3 h	198 (79,2%)	165	33 (16,7%)	52 (20,8%)	31	21 (40,4%)

Note: 1. The mass of suspended solids m_1 is given in Table 1.

The analysis demonstrated that up to 56.8% of the suspended solids settle within the first 5 minutes, and up to 76.8% within 1 hour; any further increase in settling time does not result in a significant improvement in treatment quality. This indicates the presence of stable colloidal systems, which necessitate reagent treatment.

To evaluate the treatment efficiency, the settling processes were modeled under reagent-free conditions.

The analysis of the suspended solids settling processes in pipe-rolling wastewater without the addition of reagents was performed on Sample No. 4 (see Table 4), since an open-loop water supply system operates in this workshop (thereby eliminating the influence of recycled pollutant loads).

Calculations of the average values of the settling velocity and the sizes of settled particles for various sample settling times were performed. The results are presented in Table 5.

Table 5. Calculation of settling velocity and settling efficiency

Time, s	Average settling velocity, mm/s	Calculated average particle diameter d , μm	Wastewater treatment efficiency	
			suspended solids M_1/m_1 , %	for organic matter, $(1 - M_6/m_3)$ %
0	-	-	-	-
20	0,7	19,2	23	14,8
300	0,08	6,5	57	46,3
3600	0,02	3,2	77	61,1

After 1 hour of settling under ideal laminar conditions, the proportion of settled suspended solids in the wastewater sample from pipe-rolling plant No. 2 is 77%, with settled organic matter accounting for 61.1%.

According to the data in Table 4, increasing the settling time for wastewater samples not treated with a coagulant beyond 1 hour does not result in further organic matter removal, and the settling of suspended solids practically ceases. The clarified water of the samples remains turbid, which can be

attributed to the microscopic size of the suspended particles interacting with organic matter (micelle formation).

To intensify the treatment processes, experiments were conducted using a coagulant (FeCl_3), an anionic flocculant (Ecofloc A-19), and weighting agents (microsand, magnetite).

Experimental parameters: coagulant dosage: 0.1–0.15 mL per 100 mL of sample; flocculant dosage: 0.3 mL per 100 mL; weighting agent dosage: 0.1–1 g per 100 mL. The results are presented in Table 6.

Table 6. Effect of reagents on settling velocity and treatment efficiency

No.	Reagent and dosage	Settling velocity $V = H_{\text{sample}}/\tau$, mm/s	Clarification efficiency, %	Note
1	FeCl ₃ coagulant (10% sol.), dosage: 0.15 mL/100 mL sample	$V_1 = 0,49$ $V_2 = 0,06$	99	The clarified water is clear. The settling of two types of suspended solids with different settling velocities, V_1 and V_2 , is observed
2	Anionic flocculant Ecofloc A-19, dosage: 0.3 mL/100 mL sample	1	80	The clarified water is turbid.
3	FeCl ₃ coagulant (10% solution), dosage: 0.1 mL/100 mL of sample; Anionic flocculant Ecofloc A-19, dosage: 0.3 mL/100 mL of sample	$V_1 = 2$ $V_2 = 1$	99	The clarified water is clear. The settling of two types of suspended solids with different settling velocities, V_1 and V_2 , is observed
4	Coagulant; Weighting agent: microsand (dosage: 1 g/100 mL of sample); Anionic flocculant: Ecofloc A-19 (dosage: 0.3 mL/100 mL of sample).	$V_1 = 10$ $V_2 = 2,2$	80	The clarified water is turbid; fine suspended solids are present (Photo 3a).
5	Coagulant: FeCl ₃ (10% solution), dosage: 0.1 mL/100 mL of sample Weighting agent: microsand, dosage: 1 g/100 mL of sample Anionic flocculant: Ecofloc A-19, dosage: 0.3 mL/100 mL of sample	$V_1 = 10$ $V_2 = 1,35$	99	The clarified water is clear. The settling of two types of suspended solids with different settling velocities, V_1 and V_2 , is observed. The sediment is structured (Photo 3b).
6	Coagulant: FeCl ₃ (10% solution), dosage: 0.1 mL/100 mL of sample; Weighting agent: magnetite, dosage: 1 g/100 mL of sample; Anionic flocculant: Ecofloc A-19, dosage: 0.3 mL/100 mL of sample.	$V_1 = 11$ $V_2 = 1,4$	99	The clarified water is clear. The settling of two types of suspended solids with different settling velocities, V_1 and V_2 , is observed. The sediment is structured (Photo 3c).
7	Coagulant: FeCl ₃ (10% solution), dosage: 0.1 mL/100 mL of sample; Weighting agent: microsand, dosage: 0.1 g/100 mL of sample; Anionic flocculant: Ecofloc A-19, dosage: 0.3 mL/100 mL of sample.	$V_1 = 4,2$ $V_2 = 0,6$	99	The clarified water is clear. The settling of two types of suspended solids with different settling velocities, V_1 and V_2 , is observed. The sediment is structured.
8	Coagulant: FeCl ₃ (10% solution), dosage: 0.1 mL/100 mL of sample; Weighting agent: magnetite, dosage: 0.1 g/100 mL of sample; Anionic flocculant: Ecofloc A-19, dosage: 0.3 mL/100 mL of sample.	$V_1 = 5,6$ $V_2 = 0,7$	99	The clarified water is clear. The settling of two types of suspended solids with different settling velocities, V_1 and V_2 , is observed. The sediment is structured.

It has been established that the application of flocculant alone is insufficiently effective. Coagulation with FeCl₃ achieves up to 99% clarification, while maximum efficiency is attained

through the combined use of a coagulant, flocculant, and a weighting agent. This combination results in the formation of a structured sediment with a high settling velocity (up to 10–11 mm/s).

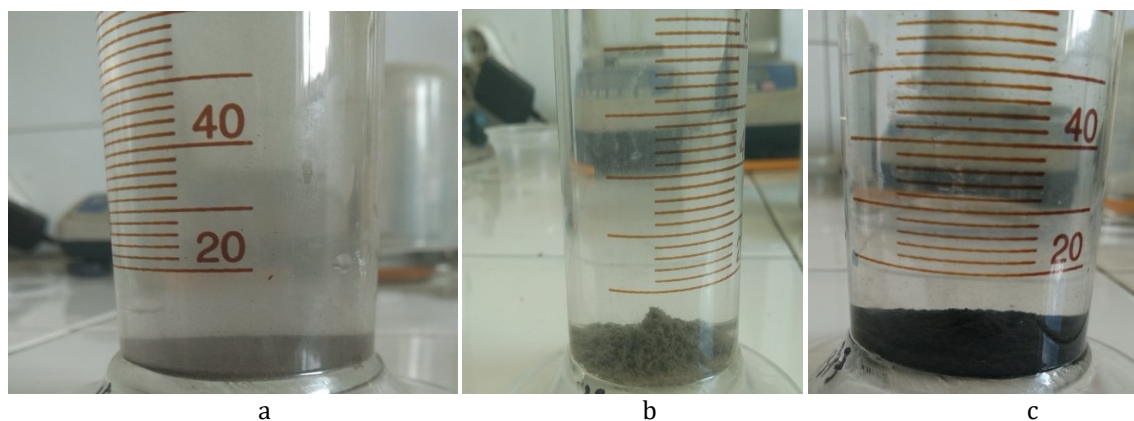


Figure 3: Photos of the clarified water: (a) turbid; (b) clear, structured sediment; (c) clear, structured sediment.

Based on the experimental data, a wastewater treatment process flow diagram has been developed (Fig. 4).

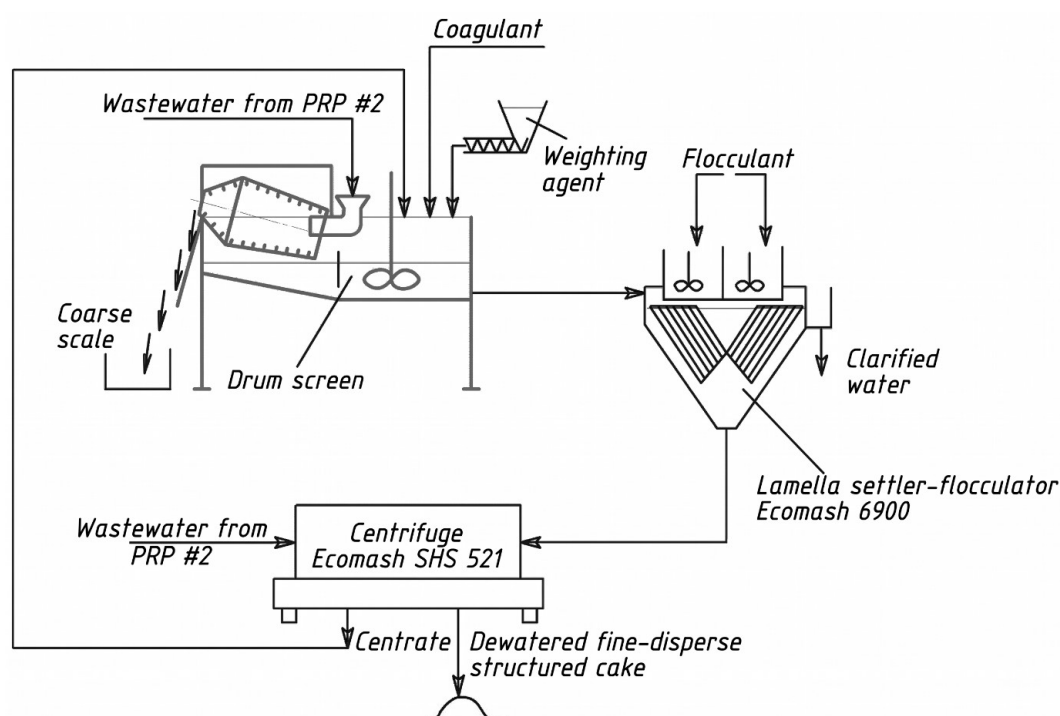


Figure 4: Recommended wastewater treatment process flow diagram for pipe-rolling production.

Based on laboratory testing of operational modes (Table 6) to intensify wastewater treatment and sludge dewatering, a two-stage wastewater treatment system is recommended (Fig. 4). This system ensures an effluent quality with suspended solids up to 20 mg/L and organic matter up to 5 mg/L:

- Stage 1: A drum screen with a capacity of $\sim 400 \text{ m}^3/\text{h}$, providing dewatering and classification of coarse scale (drum screen mesh size: $0.7 \times 0.7 \text{ mm}$).
- Stage 2: A lamella settler-flocculator with a capacity of: $400 \text{ m}^3/\text{h}$ at a suspended solids settling velocity of 5 mm/s in laboratory glassware; $600 \text{ m}^3/\text{h}$ at a suspended solids settling velocity of 10 mm/s in laboratory glassware.

Dewatering equipment: A drum screen and an Ecomash SHS 521 decanter centrifuge.

4. Conclusions

It was established that wastewater from pipe-rolling production is characterized by a complex dispersed composition and contains significant concentrations of suspended solids, scale, and petroleum products. A major portion of the pollutants consists of fine and colloidal particles, which results in high aggregative stability and complicates treatment processes.

It was demonstrated that traditional mechanical treatment methods (settling) are primarily effective for removing coarse impurities. Under reagent-free conditions, the suspended solids removal efficiency reaches approximately 77% after 1 hour, beyond which the settling process practically ceases, indicating the presence of stable colloidal systems.

It was determined that the bulk of the scale consists of coarse fractions ($>1000\ \mu\text{m}$); however, fine and ultrafine particles, which remain suspended and cause the turbidity of the treated water, have a decisive impact on treatment quality.

Experimental results confirmed that applying chemical treatment methods (coagulation and flocculation) significantly increases treatment efficiency. The use of FeCl_3 coagulant combined with an anionic flocculant achieves up to 99% clarification efficiency, reducing the concentration of suspended solids to $\sim 3\ \text{mg/L}$ and petroleum products to $\sim 1\ \text{mg/L}$.

It was established that the additional application of weighting agents (microsand, magnetite) promotes the formation of dense, structured flocs, which significantly increases the settling velocity (up to $10\text{--}11\ \text{mm/s}$) and improves sludge compaction processes.

Based on the conducted research, a two-stage wastewater treatment process flow diagram is proposed, which includes the mechanical removal of coarse scale (using a drum screen) and chemical treatment in a lamella settler-flocculator.

The obtained results confirm the feasibility of applying intensified treatment technologies for wastewater from pipe-rolling production. These findings can be utilized in the modernization of existing water treatment systems to enhance their environmental and resource efficiency.

References

- [1] Strezov, V., Zhou, X., & Evans, T. J. (2021). Life cycle impact assessment of metal production industries in Australia. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-89567-9>
- [2] Khademi, H., Gabarrón, M., Abbaspour, A., Martínez-Martínez, S., Faz, A., & Acosta, J. A. (2019). Environmental impact assessment of industrial activities on heavy metals distribution in street dust and soil. *Chemosphere*, 217, 695–705. <https://doi.org/10.1016/j.chemosphere.2018.11.045>
- [3] Tost, M., Bayer, B., Hitch, M., Lutter, S., Moser, P., & Feiel, S. (2018). Metal Mining's Environmental Pressures: A Review and Updated Estimates on CO₂ Emissions, Water Use, and Land Requirements. *Sustainability*, 10(8), 2881. <https://doi.org/10.3390/su10082881>
- [4] Conejo, A. N., Birat, J.-P., & Dutta, A. (2020). A review of the current environmental challenges of the steel industry and its value chain. *Journal of Environmental Management*, 259, 109782. <https://doi.org/10.1016/j.jenvman.2019.109782>
- [5] Shestopalov, O., Briankin, O., Tseitlin, M., Raiko, V., & Hetta, O. (2019). Studying patterns in the flocculation of sludges from wet gas treatment in metallurgical production. *Eastern-European Journal of Enterprise Technologies*, 5(10 (101)), 6–13. <https://doi.org/10.15587/1729-4061.2019.181300>
- [6] Kato, S., & Kansha, Y. (2024). Comprehensive review of industrial wastewater treatment techniques. *Environmental Science and Pollution Research*, 31(39), 51064–51097. <https://doi.org/10.1007/s11356-024-34584-0>
- [7] Bosiuk, A., Shkop, A., Kulinich, S., Samoilenko, D., Shestopalov, O., & Tykhomyrova, T. (2024). Multi-component wastewater from finely dispersed impurities treatment intensification. *Ecological Questions*, 35(4), 1–18. <https://doi.org/10.12775/eq.2024.055>
- [8] Putatunda, S., Bhattacharya, S., Sen, D., & Bhattacharjee, C. (2018). A review on the application of different treatment processes for emulsified oily wastewater. *International Journal of Environmental Science and Technology*, 16(5), 2525–2536. <https://doi.org/10.1007/s13762-018-2055-6>
- [9] López-Maldonado, E. A., Oropeza-Guzman, M. T., Jurado-Baizaval, J. L., & Ochoa-Terán, A. (2014). Coagulation–flocculation mechanisms in wastewater treatment plants through zeta potential measurements. *Journal of Hazardous Materials*, 279, 1–10. <https://doi.org/10.1016/j.jhazmat.2014.06.025>
- [10] Hayes, M. H. B., & Rouliia, M. (2025). Relevance of Organic Matter Compositions, Structures and Associations to Soil Aggregates and to Sustainable Productivity. *Agronomy*, 15(9), 2182. <https://doi.org/10.3390/agronomy15092182>
- [11] Oladoja, N. A. (2016). Advances in the quest for substitute for synthetic organic polyelectrolytes as coagulant aid in water and wastewater treatment operations. *Sustainable Chemistry and Pharmacy*, 3, 47–58. <https://doi.org/10.1016/j.scp.2016.04.001>
- [12] Pohl, A. (2020). Removal of Heavy Metal Ions from Water and Wastewaters by Sulfur-Containing Precipitation Agents. *Water, Air, & Soil Pollution*, 231(10). <https://doi.org/10.1007/s11270-020-04863-w>
- [13] Lukashenko S., Syrovatskyy O., Haiduchok O., Yarkin V., Shestopalov O., Bosiuk A., Romanchyk A., Petrescu L. (2026). Research on the treatment of meat industry wastewater by filtration combined with coagulation. *International Journal of Mechatronics and Applied Mechanics*, I(23). <https://doi.org/10.17683/ijomam/issue23.19>
- [14] Fylypchuk, V., Kalda, G., Anopolskyi, V., Fylypchuk, L., Kida, M., & AlZubi, A. A. (2026). Analysis of pressure flotation mechanisms and their practical application in the treatment of

- metal-containing wastewater. *Scientific Reports*, 16(1). <https://doi.org/10.1038/s41598-026-39418-2>
- [15] Wang, L. K., & Wang, M.-H. S. (2025). Sustainable Water and Wastewater Treatment Systems Consisting of Magnesium Coagulation-Precipitation, Dissolved Air Flotation, Recarbonation, and Filtration. *Control of Heavy Metals in the Environment*, Volume 1, 207–231. <https://doi.org/10.1201/9781003451747-8>
- [16] Wang, L. K., & Wang, M.-H. S. (2026). Wastewater Treatment and Resources Recovery in Paper and Pulp Industry. *Industrial Water and Waste Treatment*, 1–25. <https://doi.org/10.1201/9781003533566-1>
- [17] Cai, X., Guo, Y., Guan, S., Wang, D., Han, H., & Ji, Y. (2025). The separation characteristics of O/W emulsions in compact flotation unit enhanced by electrical flotation technology. *Chemical Engineering and Processing - Process Intensification*, 209, 110195. <https://doi.org/10.1016/j.cep.2025.110195>
- [18] Lee, W.-H., & Kim, J.-O. (2023). Enhanced ballasted flocculation process using magnetite-based ballast materials and a vortex flash mixer for drinking water treatment in response to both flood and dry seasons. *Chemical Engineering Journal*, 474, 145589. <https://doi.org/10.1016/j.cej.2023.145589>
- [19] Kulinich, S., Shkop, A., Bosiuk, A., & Shestopalov, O. (2025). Patterns of Aggregate Formation and Sedimentation of Fine Clay Particles. *Key Engineering Materials*, 1027, 93–100. <https://doi.org/10.4028/p-q1clxr>
- [20] Shkop, A., Kulinich, S., Shestopalov, O., Bosiuk, A., Sakun, A., Ponomarova, N., & . (2025). Intensification of the wastewater treatment process in the production of sanitary ware using coagulants and flocculants. *Environmental Problems*, 10(3), 226–236. <https://doi.org/10.23939/ep2025.03.226>