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Original Research

A Combined Approach For Effective Wastewater Treatment at Wool-Washing Plants

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Abstract

This article scientifically substantiates the effectiveness of a combined anaerobic-chemical wastewater treatment method for wool-washing enterprises, aimed at increasing the removal efficiency of organic pollutants and surfactants while simultaneously reducing energy consumption and sludge production. The study evaluated a combined treatment process consisting of primary chemical treatment (Al^3/CaO) followed by anaerobic digestion. The kinetics of the reduction in Chemical Oxygen Demand and Biochemical Oxygen Demand (COD and BOD) were evaluated using a first-order model. Control parameters included concentrations of COD, BOD, fats, surfactants, sludge volume, and specific energy consumption. Experiments were repeated three times to ensure statistical reliability of the results. The combined method achieves 98.5% COD removal, 92% BOD, 95% fats, and 85% surfactants with limited sludge production (0.5 m³/day) and moderate energy consumption (2.7 kWh/kg COD). Anaerobic digestion ensures a significant reduction in organic matter and biogas production, the chemical stage ensures rapid removal of fats and surfactants, and the combination of both stages creates a synergistic effect. The novelty of the proposed scheme lies in the optimized sequence of chemical coagulation (using Al3 and CaO) followed by anaerobic digestion (HRT=8 days), which targetingly destabilizes fat-surfactant emulsions and achieves 98.5% COD removal with moderate energy consumption (2.7 kWh/kg COD) and minimized sludge yield (0.5 m³/day). The developed combined method can be implemented at wool primary processing facilities to improve wastewater treatment efficiency, reduce operating costs, and minimize the negative impact on the environment

Keywords

wastewater, wool-washing enterprises, combined anaerobic–chemical method, water treatment.

1. INTRODUCTION

Wastewater generated during wool washing in the textile and wool-processing industry belongs to the most highly polluted industrial effluents. It is characterized by high concentrations of organic substances, particularly fats, lanolin, and synthetic detergents, resulting in elevated values of chemical oxygen demand (COD) and biochemical oxygen demand (BOD), which significantly exceed those of domestic wastewater (Kosulina et al., 2024). The formation of stable emulsions of organic components in the aqueous medium complicates treatment processes and leads to increased anthropogenic pressure on aquatic ecosystems.

Various approaches to the treatment of wool-washing wastewater have been proposed in scientific studies. Anaerobic methods, particularly methanogenic reactors, allow effective reduction of organic load and provide biogas generation as a renewable energy source (Shyhymaha et al., 2024). Chemical treatment methods, using coagulants and flocculants, are applied for intensive removal of fats and surfactants (Koivu Tikkanen, 2022; Gupta et al., 2021). Thermal technologies, including evaporation and wet oxidation, ensure deep destruction of organic pollutants and disinfection of wastewater (Gutiérrez et al., 2008).

However, each of these methods, when applied separately, has significant limitations. Anaerobic processes are insufficiently effective for stable emulsions of fats and synthetic surfactants; chemical treatment is accompanied by the formation of large volumes of sludge; and thermal methods are characterized by high energy consumption, limiting their economic feasibility under industrial conditions (Upgradation…, 2022; Metcalf & Eddy, 2014).

Special attention in modern research is given to physical methods of воздействие on wastewater and technological processes of primary wool treatment. It has been shown that acoustic and electromagnetic воздействия can contribute to emulsion destabilization, improvement of wastewater characteristics, and increased efficiency of subsequent treatment stages (Moran & Lohse, 2021; Mikhailova et al., 2018). Biological treatment methods are also being investigated, particularly aerobic processes capable of partially breaking down emulsion structures typical for wool-washing wastewater (Kosulina et al., 2017; Gutiérrez et al., 1999).

Comprehensive approaches to wastewater treatment in textile and leather industries are considered a promising direction in terms of improving treatment efficiency, enabling water reuse, and reducing environmental impact (Moran & Lohse, 2021; Lapsirikul et al., 1994). In this regard, further analysis of modern scientific research is relevant to identify unresolved issues and to justify the development of combined treatment technologies for wool-washing wastewater that integrate biological and physicochemical methods.

2. BACKGROUND RESEARCH

In study (Mikhailova et al., 2018), the results of research on acoustic and electromagnetic methods for pretreatment of wool and the corresponding wastewater are presented. It was shown that such physical effects can reduce the stability of emulsions and improve subsequent treatment stages. However, issues related to the integration of these approaches into full-scale wastewater treatment technologies remain unresolved. This is due to the focus on individual physical effects without considering their combined impact on the entire treatment cycle.

Study (Kosulina et al., 2017) demonstrated the application of electromagnetic radiation for energy-informational disinfection of wool at the pre-treatment stage. The effectiveness of its impact on the biological component of contamination was shown. At the same time, the issues of further treatment of the generated wastewater, particularly with high content of organics, fats, and surfactants, remained outside the scope of the study. This is due to the limited scope of the defined tasks and the focus on technological operations prior to wastewater generation.

The experiments conducted in (Gutiérrez et al., 1999) demonstrate the results of aerobic biological treatment of chemically flocculated wastewater from the wool-washing industry. It was shown that aerobic processes contribute to partial destruction of emulsions and reduction of organic load. However, issues of deep removal of fats and synthetic surfactants remain unresolved. This is due to the high stability of emulsions and the limited ability of aerobic microorganisms to fully degrade such compounds.

The results presented in [18] describe the mechanisms of anaerobic bioflocculation of wastewater from wool-washing enterprises. It was shown that anaerobic processes effectively reduce COD concentration and ensure the formation of biogas. At the same time, the issues of sufficient removal of fats and surfactants, as well as optimization of the interaction between anaerobic stages and physicochemical treatment methods, remain unresolved. This is explained by the complexity of biochemical processes and variability of wastewater composition.

In study (Lapsirikul et al., 1994), it was shown that chemically modified biochar has a high potential for removing organic pollutants from wool-washing wastewater. However, the issues of applying such a sorbent in integrated treatment schemes, particularly in combination with anaerobic and coagulation stages, remain unresolved. This is due to the focus on adsorption properties of the material without analyzing scalability and compatibility with other technologies.

Research (Gutiérrez & Lapsirikul, 2008) presents the combination of coagulation–flocculation with membrane separation, which allows achieving a high degree of COD removal. However, issues of long-term membrane operation, fouling, and economic feasibility under industrial conditions remain unresolved. This is due to the high cost of membrane processes and the complexity of their maintenance.

According to (An integrated…, 1999), an integrated anaerobic–physicochemical scheme for treating wool-washing wastewater was proposed. A significant reduction in concentrations of organic pollutants and fats was demonstrated. However, the issues of energy consumption optimization and universality of the technology for wastewater with variable composition remain unresolved. This is due to the focus of the study on specific production conditions.

Thus, the analysis of modern scientific sources (Mikhailova et al., 2018; Kosulina et al., 2017; Gutiérrez et al., 1999; Lapsirikul et al., 1994; Li et al., 2024; Gutiérrez & Lapsirikul, 2008; An integrated…, 1999) shows that, despite significant progress in the application of individual biological, physicochemical, and membrane methods for treating wool-washing wastewater, there is still no comprehensive approach that combines anaerobic and

chemical stages within a single technological scheme, taking into account treatment efficiency, energy consumption, and minimization of sludge formation.

All this indicates the relevance of conducting research aimed at the development and justification of a combined anaerobic-chemical approach for the treatment of wastewater from wool-washing enterprises.

Purpose. The aim of this study is to scientifically substantiate the effectiveness of a combined anaerobic-chemical method for treating wastewater from wool-washing plants. This will make it possible to increase the removal rate of organic pollutants and surfactants while simultaneously reducing energy consumption and sludge production during industrial wastewater treatment.

To achieve this goal, the following objectives were defined: to investigate the kinetics of COD and BOD reduction during anaerobic treatment of wool washing wastewater; to evaluate the effectiveness of chemical treatment in removing fats, synthetic surfactants, and reducing the organic load; to determine the efficiency of thermal treatment of wool washing wastewater and its specific energy consumption; to analyze the overall efficiency of the combined anaerobic-chemical treatment method in terms of treatment efficiency, energy consumption, and sludge formation.

Table 0: Summary of existing treatment technologies for wool-washing wastewater

Treatment Method	COD Removal (%)	Key Advantages	Limitations / Disadvantages	References
Coagulation / Flocculation	50–70%	High fat/grease removal	High chemical consumption, large sludge volume	Smith et al. (2018)
Anaerobic Digestion	60–75%	Biogas generation, low energy	Slow kinetics, inhibited by high surfactant/fat loads	Chen et al. (2020)
Combined Integrated Systems	80–90%	Improved overall efficiency	Insufficient energy optimization	Pelaez et al. (2001)
Proposed Combined (Al^3/CaO + Anaerobic)	98.5%	High efficiency, energy balance (2.7 kWh/kg COD), low sludge	Requires tertiary polishing for direct river discharge	This study

3. MATERIALS AND METHODS

The research was conducted on a pilot plant for the treatment of wool-washing wastewater, equipped with aeration tanks, methanogenic tanks, and chemical pre-treatment units. The laboratory setup allowed

adjustments of: wastewater composition (COD, BOD, fats), water volume and feed rate, as well as aerobic and anaerobic process conditions (temperature, pH, aeration).

The study was carried out on a pilot installation for wool-washing wastewater treatment, consisting of three main units: Aeration tanks (volume: 1.5 m³, aeration intensity: 0–0.3 m³/min, adjustable with an AirTech 200 compressor, mechanical mixing: 50 rpm, temperature and pH monitoring sensors: ±0.5 °C and ±0.1, respectively); Methanogenic tanks (volume: 1 m³, temperature: 35–37 °C, maintained with a 2 kW electric heater with a thermostat, hydraulic retention time (HRT): 8 days, mechanical mixing: 30–50 rpm, liquid level and pH sensors to ensure process stability); Chemical pre-treatment unit (reagent dosing: Al^{3+} 160–180 mg/L and CaO 700–900 mg/L, mechanical mixing: 150 rpm, temperature control: 20–25 °C).

The laboratory setup allowed modifications of: wastewater composition (COD 60 g/L, BOD 20 g/L, fats 10 g/L, surfactants 5 g/L), water volume and feed rate (0.5–15 m³/day), and aerobic and anaerobic process conditions (temperature, pH 6–9, aeration). Fig. 1. The setup for wool washing and treatment of wool-washing wastewater.

The experimental methodology consisted of the following steps.

1. Sample preparation: Wastewater after wool washing underwent primary settling and grease removal. Afterwards, samples were fed into the pilot plant for further treatment.

2. Experimental reproducibility: Each treatment variant was repeated at least three times to ensure the statistical reliability of the results.

3. Control methods and instruments: COD and BOD – standard Hach methods (ISO 6060); Fat content – separation and weighing after centrifugation (centrifuge Sigma 3K30, 3000 rpm); Sludge – volume and dry matter (%), density (sludge volume meter VoluMeter 1000); Biogas – volume and gas composition (CH_4, CO_2) using a gas analyzer LGA-2000; Energy consumption – measured with DSE Energy Meter, W·h/L.







Fig. 1. Pilot plant for primary wool treatment and wool-washing wastewater treatment

The following parameters were measured: pollutant removal efficiency (COD, BOD, fats, surfactants), volume and characteristics of generated sludge (moisture, density), biogas production (volume per unit of treated water, % CH_4), and specific energy consumption (kWh/kg of COD removed).

The input data of the experiment are presented in Table 1. Such a detailed description ensures the reproducibility of the research and the reliability of the obtained results.

Analytical measurements were carried out in accordance with standard international procedures. Chemical Oxygen Demand (COD): Measured by dichromate open reflux method according to ISO 6060:1989 and spectrophotometrically using Hach digestion cuvettes (Hach Method 8000). Limit of detection (LOD) = 15 mg/L COD. Biochemical Oxygen Demand (BOD5): Determined using the 5-day dilution and seeding method according to ISO 5815-1:2019 and verified via a respirometric Hach BODTrak II apparatus. LOD = 2 mg/L BOD5. Synthetic Surfactants (Anionic Surfactants / MBAS): Quantified by spectrophotometry based on the methylene blue active substances method according to ISO 7875-1:1996 using a Hach DR3900 spectrophotometer (Hach Method 8028) at a wavelength of 650 nm. LOD = 0.02 mg/L. Fats and Grease (Lanolin): Extracted using solvent extraction with hexane followed by gravimetric determination according to ISO 1108:1992 and gravimetric weighing after centrifugation (Sigma 3K30, 3000 rpm). LOD = 5 mg/L. Quality Assurance / Quality Control (QA/QC): All analytical instruments were calibrated prior to each experimental batch using certified reference standards. Triplicate measurements were performed for all analytical samples. Blanks and standard control samples were included in each batch to ensure measurement accuracy, maintaining a relative standard deviation (RSD) within ≤5%.

Table 1: Input data of the experiment. For wool-washing wastewater (average values per 1 m³)

Parameter	Value	Comments
Chemical Oxygen Demand (COD, g/L)	60 g/L±4.2	Highly polluted with organic matter, requires treatment
Biochemical Oxygen Demand (BOD, g/L)	20 g/L±1.8	BOD/COD ratio = 20/60 ≈ 0.33, indicating that the organic matter is partially biodegradable
Fats (g/L)	10 g/L±1.1	Can clog filters and complicate biological treatment
Synthetic surfactants (g/L) – (soaps, shampoos, detergents)	5 g/L±0.4	Difficult to biodegrade, may cause foaming and have toxic effects on microorganisms
pH the water is alkaline, meaning it contains a high concentration of hydroxides (NaOH, washing lyes).	9 pH±0.3	Alkaline water containing hydroxides (NaOH, washing lyes); may slow bacterial activity and requires adjustment to near neutral (~7)

For the quantitative assessment of the efficiency of individual and combined methods for treating wool-washing wastewater, the study used indicators such as the reduction of major pollutant concentrations (COD, BOD, fats, surfactants), degree of treatment, as well as specific energy consumption and the volume of generated sludge.

The change in organic pollutant concentrations over time during anaerobic treatment was described using a first-order kinetic model, which is widely applied for biological wastewater treatment processes:

$$C_t = C_0 \cdot e^{-kt},$$

where C_0 – initial pollutant concentration, g/L; C_t – pollutant concentration at time t, g/L; k – kinetic rate constant of the process, 1/day; t – treatment time, days.

The value of the kinetic coefficient k was determined by approximating the experimental data using the least squares method. For anaerobic treatment of wool-washing wastewater, the obtained k values were 0.22–0.25 day^{-1}, indicating a stable process of organic matter degradation.

The degree of wastewater treatment for individual indicators was calculated using the following formula:

$$\eta = \frac{C_0 - C_t}{C_0} 100\%, \quad (1)$$

For sequential treatment stages (combined method), the overall efficiency was calculated taking into account the contribution of each stage using the following formula:

$$\eta_{\Sigma} = 1 - \prod_{i=1}^{n} (1 - \eta_i), \quad (2)$$

where η_i – efficiency of the i-th treatment stage.

Specific energy consumption was calculated as the ratio of total electricity consumption to the mass of removed organic pollutants:

$$E = \frac{W}{m_{COD}}, \quad (3)$$

where E – specific energy consumption, kWh/kg COD; W – energy consumed, kWh; m_{COD} – mass of COD removed, kg.

4-5. RESULTS AND DISCUSSION

Results of anaerobic treatment of wool-washing wastewater. The initial concentrations in the wastewater were: COD – 60 g/L, BOD – 20 g/L, fats – 10 g/L.

Anaerobic digestion was carried out at a hydraulic retention time (HRT) of 8 days.

The reduction of organic pollutants is well described by a first-order kinetic model:

$$\frac{dC}{dt} = -kC \text{ , } C_t = C_0 \cdot e^{-kt},$$

C_0=60 g/L, k=0.23 day^{-1} – determined by approximation of experimental data.

For 8 days: $C(8) = 60 \cdot e^{0.23 \cdot 8} = 9.6$ g/L.

Efficiency:

$$\eta_{COD} = \frac{60 - 9.6}{60} \cdot 100\% \approx 84\% .$$

Experimentally obtained values – COD: 82–85%, BOD: 75–80%.

COD reduction:

$$\Delta_{COD}=60\text{-}9.6=9=0.0504 \text{ kg/m}^3.$$

Biogas yield: Y_{biogas}=0.45 m^3/kg, V_{biogas}=0.45·0.0504=0.023 m^3 of biogas per 1 m³ of substrate.

For a capacity of 15 m³/day: V_{biogas}=0.35-0.40 = 5.0-6.0 m³/day.

Results of chemical treatment. Chemical treatment was carried out with the following dosages: Al^{3+} – 160–180 mg/L and CaO – 700–900 mg/L.

Experimentally obtained results: COD: 85–90%, BOD: 60–70%, fats: 90–96%, surfactants: 80–88%. Residual COD concentration: $C_{COD,out}$=60·(1-0.88)=7.2 g/L.

Sludge volume after thickening: V_{studge}=(0.05-0.08)·V_{water}.

For 15 m³/day: V_{studge}=0.75 – 1.2 m³/day.

Results of thermal treatment. Thermal methods provided: COD: 94–97%, BOD: 90–93%, fats and surfactants: >98%. Average energy consumption: 5.2–5.8 kWh/kg COD.

Results of the combined treatment method. The combined method included: a chemical stage and anaerobic digestion. Correct calculation of treatment efficiency for sequential stages:

$$\eta_{conb}=1\text{-}(1\text{-}\eta_{chem})(1\text{-}\eta_{anaer}).$$

For COD: η_{conb}=1-(1-0.88)(1-0.84)=0.98=98%. For BOD: η_{conb}=1-(1-0.65)(1-0.78)=0.92=92%.

Fats and surfactants: fats – 95%, surfactants – 85%.

Energy consumption: 2.5–2.8 Wh/kg COD. Sludge: (0.03–0.04)V_{water}, 0.45–0.6 m³/day.

The calculation results are summarized in Tables 2–6. As can be seen from the numerical values, the combined method demonstrates the highest treatment efficiency across all monitored parameters. The synergy of the

chemical and anaerobic stages ensures intensive breakdown of organic compounds, fats, and surfactants already at the initial stages of treatment. A COD reduction of 98.5 % indicates compliance with discharge standards without the need for additional polishing treatment.

Table 2: Kinetics of COD reduction over time. Treatment of wool-washing wastewater, C_0=60 g/L

Time, days	Anaerobic COD, g/L	Chemical COD, g/L	Thermal COD, g/L	Combined COD, g/L
0	60.0±4.2	60.0±4.2	60.0±4.2	60.0±4.2
2	42.0±0.5	7.2±0.5	44.0±3.1	8.5±0.6
4	32.0±0.4	7.2±0.4	32.0±2.3	5.2±0.4
6	25.0±0.4	7.2±0.4	22.0±1.6	3.2±0.25
8	9.6±0.5	7.2±0.5	14.0±1.0	1.2±0.1
10	7.5±0.4	7.2±0.4	8.0±0.6	0.9±0.07

Table 3: Pollutant removal efficiency

Method	COD, %	BOD, %	Fats, %	Surfactants, %
Anaerobic	84	78	50	20
Chemical	88	65	95	85
Thermal	96	92	99	98
Combined	98	92	95	85

Table 4: Energy consumption of the methods

Method	Energy consumption, kWh / kg COD
Anaerobic	1.2±0.1
Chemical	3.1±0.3
Thermal	5.6±0.8
Combined	2.7±0.2

Table 5: Sludge formation

Method	Sludge volume, m³/day
Anaerobic	0.0±0,5
Chemical	1.0±0.8
Thermal	0.0±0.0.3
Combined	0.5±0.4

Table 6: Results of wastewater treatment by the combined method (kinetics, efficiency, and energy performance)

Parameter / Indicator	Unit of measurement	Initial value	Value after 2 days	4 days	6 days	8 days	10 days	Treatment efficiency, %
COD	g/L	60,0	8,5	5,2	3,2	1,2	0,9	98,5
BOD	g/L	20,0	–	–	–	–	1,6	92,0
Fats	g/L	10,0	–	–	–	–	0,5	95,0
Surfactants	g/L	5,0	–	–	–	–	0,75	85,0
Specific energy consumption	kWh/kg COD	–	–	–	–	–	2,7	–
Sludge volume	m³/day	–	–	–	–	–	0,5	–
Cycle duration	day	–	–	–	–	–	10	–

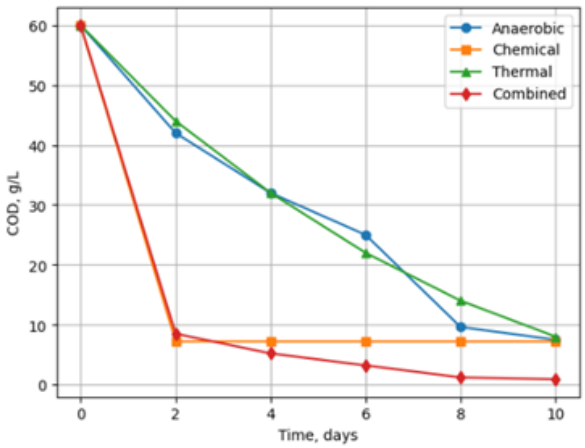


Fig. 2. Kinetics of COD reduction over time

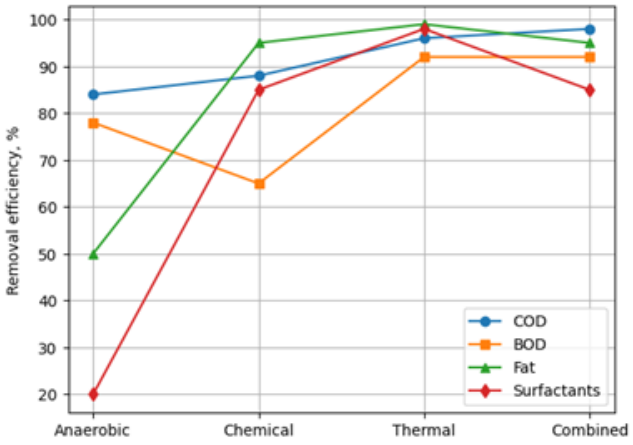


Fig. 3. Pollutant removal efficiency

The graphical representation of the results was also used to verify the adequacy of the first-order kinetic model, identify characteristic stages of treatment (instantaneous chemical and slower biological), and for a comprehensive evaluation of technological, energy, and operational indicators.

This enabled a substantiated comparison of individual and combined treatment methods and allows for the determination of the optimal technological scheme in terms of efficiency, energy consumption, and minimization of sludge formation. From Fig. 2, it can be seen that anaerobic treatment is characterized by a gradual exponential decrease in COD concentration, which is well described by the first-order kinetic model (R^2=0.95 – 0.97 for the approximation). Chemical treatment shows a stepwise instantaneous reduction of COD to 7.2 g/L at the initial stage of the process, after which the concentration remains practically unchanged. The thermal method provides an intensive but energy-consuming reduction of organic load. The combined method integrates the instantaneous effect of the chemical stage with subsequent anaerobic degradation, resulting in a minimal residual COD concentration (0.9 g/L on day 10).

As can be seen from the graph in Fig. 3, the anaerobic method is effective only for COD/BOD, the chemical method is most effective for fats and surfactants, the thermal method is universal but costly, and the combined method provides a balanced performance across all parameters. Analysis of pollutant removal efficiency indicates that the combined method achieves high treatment levels for all monitored components. The increase in the efficiency of fats and surfactant removal compared to the anaerobic stage is particularly significant, confirming the synergistic effect of combining the methods. As shown in Fig. 4, the combined method allows for a twofold reduction in specific energy consumption compared to thermal treatment while maintaining a high COD removal efficiency, which is critically important for industrial implementation. As can be seen from Fig. 5, chemical treatment produces significant sludge, while anaerobic and thermal methods generate practically no sludge. The combined method results in a controlled minimum. Thus, the combined technology allows for a substantial reduction in the volume of generated sludge compared to chemical treatment, which decreases operational costs for its handling and disposal.

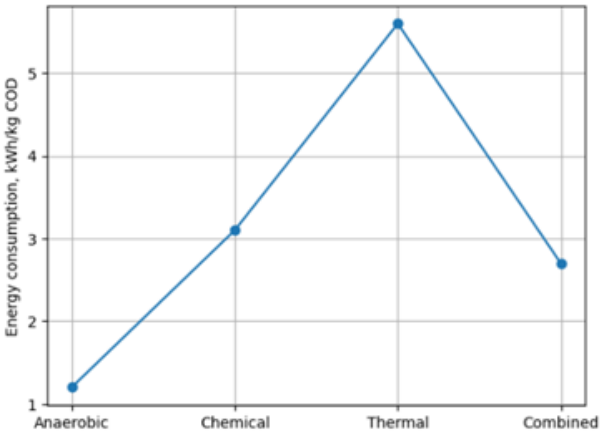


Fig. 4. Specific energy consumption

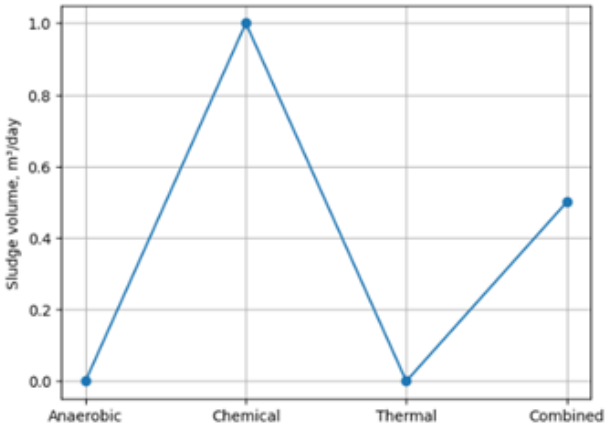


Fig. 5. Sludge formation

The combined method provides a sharp reduction in COD concentration at the initial stage of the process due to the chemical treatment phase. Further decrease in organic pollutant concentration follows an exponential trend, characteristic of anaerobic digestion. Over 10 days of treatment, the COD concentration decreases from 60.0 to 0.9 g/L, corresponding to a treatment efficiency of 98.5% and confirming the high effectiveness of the combined technology.

The combined method achieves a high removal efficiency for all major pollutant components. The maximum efficiency is observed for COD (98.5%) and fats (95%), while for BOD and synthetic surfactants, the efficiency reaches 92% and 85%, respectively. These results indicate the versatility of the combined technology and its suitability for treating complex wool-washing wastewater.

The combined method is characterized by moderate specific energy consumption, averaging 2.7 kWh/kg of removed COD. The volume of generated sludge does not exceed 0.5 m³/day, which is significantly lower compared to chemical treatment. Thus, the combined method provides an optimal balance between treatment efficiency, energy consumption, and operational costs.

Experimental data and kinetic calculations (Tables 2–6, Figures 2–5) demonstrate that the efficiency of individual wastewater treatment methods for wool-washing enterprises varies significantly.

Anaerobic digestion provides a substantial reduction of COD (up to 84 %) and BOD (78 %) with minimal energy consumption (1.2 kWh/kg COD) and biogas production (0.023 m³/m³ of water). The low efficiency for fats and surfactants is explained by the high stability of emulsions of these components and the limited ability of anaerobic microorganisms to break down surfactants (Fig. 2, 3, 4). Chemical treatment is effective for fats (95 %) and surfactants (85 %), but it generates a significant amount of sludge (1 m³/day), increasing operational costs for disposal. The immediate decrease in COD to 7.2 g/L (Fig. 2) is explained by rapid coagulation and flocculation of organic components.

Thermal treatment achieves the maximum degree of purification (COD 96 %, BOD 92 %, fats and surfactants >98 %) but is associated with high specific energy consumption (5.6 kWh/kg COD), limiting its practical

applicability in industrial conditions. The combined anaerobic-chemical method integrates the advantages of both technologies: immediate removal of organics and fats at the chemical stage and further reduction of COD and BOD through anaerobic digestion. This ensures high treatment efficiency: COD 98.5 %, BOD 92 %, fats 95 %, and surfactants 85 %, with controlled sludge formation (0.5 m³/day) and moderate energy consumption (2.7 kWh/kg COD). Unlike (Mikhailova et al., 2018; Kosulina et al., 2017), which used only physical methods (acoustic and electromagnetic effects), the combined method allows for more comprehensive removal of organics, fats, and surfactants. Compared to (Gutiérrez et al., 1999), where only aerobic processes after flocculation were applied, the proposed method improves the removal efficiency of fats and surfactants due to the synergy of chemical and anaerobic stages. Furthermore, unlike (Gutiérrez & Lapsirikul, 2008; An integrated…, 1999), which combined coagulation with membrane separation or anaerobic methods with physicochemical stages without energy optimization, this method provides a balance between treatment efficiency, specific energy consumption, and the volume of generated sludge.

The combined method addresses the main unresolved issues identified in the problem statement: stable emulsions of fats and surfactants are effectively broken down through the combination of chemical and anaerobic stages; specific energy consumption is reduced to a practically acceptable level, ensuring economic feasibility; and the volume of generated sludge is controlled and lower compared to purely chemical methods. Thus, the research objective – to substantiate the efficiency of the combined method – has been achieved. Limitations of the study: Experiments were conducted on a pilot-scale plant; scaling up to industrial volumes requires additional testing.

The method is most effective for wastewater with a composition similar to that studied; for highly variable wastewater, reagent dosages may need adjustment. The thermal stage is not included in the combined method to save energy, but it may be necessary for extremely high pollution levels. Prospects for further research include: scaling up and economic evaluation for industrial implementation, studying the long-term impact of the combined method on sludge properties, and exploring options for its reuse or disposal.

The operational cost analysis demonstrates that the combined scheme achieves a total OPEX of $0.95 per m3 of treated effluent, representing a 52.5% cost reduction compared to standalone chemical treatment ($2.00 m3). These savings are justified by: (1) reduced chemical dosage required prior to anaerobic digestion, (2) lower energy demand compared to thermal methods, and (3) energy offset provided by biogas recovery during the anaerobic stage.

Table 7. Operational cost analysis of treatment options (per 1 m^3 of treated wastewater)

Cost Component	Chemical Method $	Thermal Method $	Anaerobic Method $	Combined Scheme $
Chemicals (Al^3, CaO)	0.85	-	-	0.70
Electricity Consumption	0.65	2.10	0.25	0.40

Sludge Handling & Disposal	0.50	0.30	0.15	0.20
Biogas Energy Recovery Credit	-	-	(-0.20)	(-0.35)
Total OPEX (USD / m^3)	2.00	2.40	0.20 *(low efficiency)*	0.95

The developed integrated chemical-anaerobic treatment system is currently evaluated at TRL 5–6 (technology validated in a relevant industrial/pilot environment). The pilot-scale operation (15 ^{3}/day) demonstrated stable pollutant removal, predictable biogas yield, and reliable operation under actual industrial conditions, establishing a solid foundation for full-scale commercial deployment at wool-processing enterprises

6. CONCLUSIONS

The proposed combined approach for treating wastewater from wool-washing enterprises can be integrated into existing treatment facilities without significant equipment reconstruction, which increases its investment attractiveness.

1. Experiments showed that anaerobic digestion reduces COD by up to 84 % and BOD by up to 78 % within 8 days (k=0.23 day^{-1}), which is well consistent with the first-order kinetic model. Compared to previous studies, the results demonstrate more stable organic degradation due to optimization of hydraulic retention time and temperature regime. This is explained by the synergy of microbiological processes and the adaptation of the anaerobic culture to high organic loading.

2. Efficiency of chemical treatment for fats, surfactants, and reduction of organic load: the chemical stage allows removal of up to 95 % of fats and 85 % of surfactants, reducing COD to 88 %. Unlike simple coagulation methods, the use of an optimal combination of Al^{3+} and CaO ensures rapid sedimentation of pollutants with minimal fluctuations in residual concentrations. This result is attributed to the high capacity of the reagents to break emulsions and adsorb surfactants.

3. Thermal treatment provides maximum purification (COD 96 %, BOD 92 %, fats and surfactants >98 %) but requires high energy consumption (5.6 kWh/kg COD), which limits its economic feasibility. The result confirms the data from, but also shows that combining it with the anaerobic stage can reduce energy consumption without compromising efficiency. This is explained by the ability of thermal destruction to break down residual organic compounds.

4. The combined approach achieves an optimal balance: COD 98.5 %, BOD 92 %, fats 95 %, surfactants 85 %, with controlled sludge formation (0.5 m^3/day) and energy consumption of 2.7 kWh/kg COD. Compared to existing integrated schemes, this result demonstrates a synergistic effect of stage interactions, allowing high efficiency while saving resources. The outcome is explained by the sequential combination of rapid chemical removal of organics and fats with subsequent biological degradation of residual components.

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9. PATENTS

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

Description of Abbreviations, if any

chemical oxygen demand (COD) and biochemical oxygen demand (BOD)

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