RESEARCH ON THE TREATMENT OF MEAT INDUSTRY WASTEWATER BY FILTRATION COMBINED WITH COAGULATION

Serhii Lukashenko[1] [0009-0001-2052-1183], Oleksandr Syrovatskyy[1] [0000-0003-1002-8579], Oleksandr Haiduchok[1] [0000-0003-3139-9061], Vadim Yarkin[1] [0000-0001-7844-6772], Oleksii Shestopalov[2] [0000-0001-6268-8638], Alona Bosiuk[2] [0000-0001-5254-2272], Andrii Romanchyk[2] [0009-0007-1660-4676], Ligia-Luminița Petrescu[3] [0009-0007-5746-506X]
[1]O.M. Beketov National University of Urban Economy in Kharkiv
[2]National Technical University "Kharkiv Polytechnic Institute"
[3]The National Institute of Research and Development in Mechatronics and Measurement Technique (INCDMTM)
Email: Alona.Bosiuk@mit.khpi.edu.ua

Abstract - Meat processing enterprises generate significant volumes of fatty wastewater with high fat content (600–2000 mg/L), suspended solids (600–2000 mg/L) and chemical oxygen demand (COD 1000–2600 mg/L). Traditional local treatment methods (grease traps, sedimentation tanks, flotation) do not always ensure compliance with regulatory requirements for discharge into municipal sewers (fats ≤ 20–100 mg/L, suspended solids ≤ 500 mg/L, COD ≤ 1000 mg/L), which complicates the operation of municipal treatment facilities. The paper investigates the effectiveness of treating such effluents by pressure filtration through elastic polyurethane foam (EPU) in combination with chlorine iron coagulation and sedimentation. A two-stage scheme is proposed: preliminary filtration through EPPU – coagulation ($FeCl_3$ dose 100–200 mg/L, optimally 150 mg/L) with polyacrylamide flocculation (3–5 mg/L) – settling for 30 minutes – repeated filtration through EPPU. Experiments have shown that at a filtration rate of 5–15 m/h, a bed height of 2 m and a density of 50 kg/m^3, the fat content is reduced by 97.3–99.1%, suspended solids by 94.1–96.6%, COD by 52.0–74.6%. After a full treatment cycle, the wastewater parameters are as follows: fats 19 mg/L, suspended solids 54 mg/L, COD 630 mg/L, BOD_5 470 mg/L, which meets the requirements for discharge into the municipal sewerage system. Based on experimental design and regression analysis, mathematical dependencies were obtained that allow predicting the concentration of contaminants in treated water and the duration of the filter cycle depending on the initial parameters (filtration rate, concentrations of fats, suspended solids, COD). The proposed technology ensures high efficiency, compact equipment and the possibility of repeated use of EPPU after mechanical regeneration, which makes it promising for local treatment systems of meat processing enterprises.

Keywords: Fatty wastewater, Elastic polyurethane foam, Coagulation, Filtration, Settling, Meat industry.

1. Introduction

In the technological processes of meat-processing enterprises, water is used for washing products, equipment, and utensils; cooling apparatuses and machines; transporting technical raw materials; and preparing reagents. Up to 30–40% of the total wastewater volume generated by these enterprises is characterized by elevated contents of fats, suspended solids, and dissolved organic compounds. The concentrations of fats and suspended solids in wastewater from the meat industry in Ukraine and in developed countries typically range from 600 to 2000 mg/L, while the chemical oxygen demand (COD) ranges from 1000 to 2600 mg/L [1–5].

According to the requirements for the composition of wastewater from meat-processing enterprises when discharged into municipal sewerage systems, the permissible fat content is 20–100 mg/L, suspended solids up to 500 mg/L, and COD not exceeding 1000 mg/L [6–7]. It is worth noting that these standards have become increasingly stringent over time. This necessitates preliminary on-site treatment of technological effluents at enterprises to ensure compliance with current requirements [7].

dx.doi.org/10.17683/ijomam/issue23.19

Treatment facilities operating at meat-processing plants-such as grease traps, sedimentation tanks, and flotation units – do not always provide an adequate level of wastewater treatment. The insufficient efficiency of these systems leads to complications during subsequent treatment at municipal wastewater treatment plants, since the substances present in effluents from meat-processing enterprises are poorly removed by conventional biological oxidation processes [8].

The use of filtration through conventional granular media to improve the treatment quality of such wastewater has also not gained practical application in Ukraine or abroad, due to the lack of effective methods for regenerating the filter media [2–4].

A promising direction for improving wastewater treatment technologies for effluents with high contents of fats and suspended solids is the application of filters packed with oleophilic synthetic materials, such as polyurethane foam, expanded polystyrene, and shredded foam plastics [9].

Studies show that elastic polyurethane foam effectively sorbs fats due to its porous structure, allowing for an 80-95% reduction in fat concentration at a loading density of 40-60 kg/m^3, making it ideal for combined systems with coagulation [33] and making it suitable for integration into automated, sensor-controlled systems typical of mechatronic engineering applications.

The use of these materials enhances the efficiency of pollutant retention, improves the operational reliability of local treatment facilities, and reduces the overall dimensions of treatment equipment at meat-processing enterprises.

2. Analysis of Literature Data and Problem Statement

Studies of the composition and characteristics of wastewater from meat-processing enterprises conducted in various countries indicate that such effluents belong to Hazard Class II, are characterized by high pollutant concentrations, and create favorable conditions for the development of microorganisms, including putrefactive and pathogenic species [1–4]. Therefore, on-site (local) treatment of such wastewater, followed by the utilization of the removed fats, is a necessary component of the wastewater disposal system [1–3, 10–11].

A significant fraction of pollutants in wastewater from meat-processing plants is present in the form of stable suspensions and emulsions, which are difficult to separate and cannot be efficiently removed without the application of chemical (reagent) treatment. The concentration of dissolved organic substances typically ranges from 420 to 1240 mg/L [7, 12–13].

In industrial practice, a three-stage wastewater treatment scheme is most commonly applied, comprising mechanical, physicochemical, and biological treatment stages [8, 10, 13].

The mechanical treatment block usually includes screens and grit chambers installed upstream of sedimentation tanks. The removal efficiency of fats and suspended solids in grit chambers is approximately 10–15%, whereas in sedimentation tanks, it reaches 30–50%. COD and BOD removal efficiencies remain practically unchanged, as their reduction primarily occurs due to the removal of solid particles and fats rather than dissolved organic matter [11].

Sedimentation-type grease traps are typically designed for a detention time of approximately 30 minutes. The fat removal efficiency is 50–55%, of which about 20–25% is removed together with the settled sludge, while approximately 30% accumulates on the water surface. Subsequently, the recovered fat mass is either disposed of or utilized [10, 13].

In recent years, several effective methods and technological solutions have been developed for on-site wastewater treatment from meat-processing enterprises, specifically to remove protein compounds, fats, and other suspended solids. In particular, the feasibility and effectiveness of flotation methods for treating industrial effluents from the meat industry have been investigated [3, 14]. The positive results of these studies provided the basis for the development and implementation of various flotation-based wastewater treatment systems.

Treatment units for fat-containing wastewater that combine flotation and oxidation processes have been developed. Currently, several types of flotation systems are used in the practice of meat-processing enterprises, including impeller flotation [11], dissolved air flotation (DAF) [14], and electroflotation [3, 15]. There are also reports on the application of foam separation for removing impurities from wastewater [3].

The application of impeller and dissolved air flotation without prior coagulation makes it possible to achieve fat removal efficiencies of 40–60%, suspended solids removal of 40–50%, and COD reduction of 30–35% [14]. Experimental studies on the electroflotation treatment of fat-containing wastewater, as well as investigations into electroflotocoagulation processes, have contributed to the development of units designed for the preliminary treatment of effluents from meat-processing plants before discharge into municipal sewerage systems [15].

The electroflotation method has proven to be fairly effective; however, even after its application, a significant amount of contaminants remains in the treated water, including fats at 100–300 mg/L, suspended solids at 200–400 mg/L, and COD values in the range of 700–1000 mg/L [3]. Design-related drawbacks of electroflotators currently limit the wider adoption of electroflotation technology. An analysis of wastewater treatment results from meat-processing plants using various flotation methods (without coagulation) has shown that all of them provide approximately the same efficiency—about 50–60% in terms of fat and suspended solids removal [3, 11, 14–15].

Recent studies confirm that the combination of filtration through EPPU with coagulation allows for up to 98% fat removal efficiency at a filtration rate of 5–10 m/h, with an emphasis on optimising loading density to reduce head loss [34]. Such systems lend themselves well to mechatronic enhancements, including automated flow regulation, real-time turbidity/pressure monitoring, and adaptive coagulant dosing based on sensor feedback.

An analysis of patent sources and scientific and technical literature indicates that, both in Ukraine and abroad, the application of coagulation-based treatment methods is advisable for the advanced (deep) treatment of wastewater from meat-processing enterprises [16–19]. Inorganic salts, such as iron and calcium chlorides [18], iron and aluminum sulfates [17], as well as various organic and inorganic coagulants, are typically used [19]. In addition, the use of surfactants is recommended to enhance process efficiency [16].

Research has shown that the use of salts of polyvalent metals, particularly ferric chloride, as reagents in the coagulation process ensures not only high treatment efficiency but also enables the recovery and reuse of valuable raw-material components contained in wastewater [17–18]. When flotation is combined with coagulation for the treatment of fat-containing effluents, a high degree of purification is achieved: 93–98% for fats, 85–96% for suspended solids, and 50–86% for COD [14, 18].

Thus, summarizing the available data, it can be concluded that physicochemical treatment methods provide substantial removal efficiencies for the main indicators: fat reduction of 50–84%, suspended solids reduction of 50–70%, and COD and BOD reduction of 50–60%. In some cases, even higher treatment efficiencies are achieved, with fat removal of up to 98%, suspended solids removal of up to 95%, and COD reduction of up to 86% [16–18].

According to literature data, after sedimentation, the concentration of fats in wastewater ranges from 100 to 500 mg/L, while suspended solids reach up to 900–1000 mg/L. COD and BOD values are in the range of 1000–1300 mg/L [20–23]. The highest treatment efficiencies are achieved at biological treatment and advanced polishing facilities, where fat removal reaches 99–100%, suspended solids removal 95–98.2%, and total biochemical oxygen demand (BOD_{tot}) is reduced by 97–99.5% [20–22]. At the same time, studies confirm the effectiveness of combining biological treatment methods with membrane technologies [23].

An analysis of existing data on the efficiency of fat and suspended solids removal from fat-containing wastewater using conventional methods (sedimentation, flotation, biological, and chemical treatment) shows that none of these methods alone ensures full compliance with the requirements for wastewater discharged into municipal sewerage systems. In addition, on-site treatment facilities require substantial land areas, high reagent consumption, and significant energy inputs.

In this regard, further research on the use of elastic polyurethane foam (EPUF) in combination with other physicochemical wastewater treatment methods at local treatment facilities of meat-processing enterprises is considered highly relevant, with the aim of subsequent discharge into municipal sewerage systems. The application of the proposed treatment schemes should ensure high efficiency and compactness of treatment systems while simultaneously reducing energy and resource consumption.

The aim of this study is to develop a scientifically substantiated wastewater treatment scheme for the meat-processing industry and to determine the governing patterns and design parameters of the treatment process for fat-containing wastewater using filtration through elastic polyurethane foam (EPUF) in combination with coagulation and sedimentation. To achieve this aim, the authors addressed the following objectives: identification of the key parameters influencing the filtration process, assessment of their mutual interactions, selection of the coagulant type and dosage, and derivation of design relationships suitable for engineering calculations under real industrial operating and design conditions.

3. Research Methodology

As demonstrated by the results of experimental studies presented in our previous works [24–27], filtration of fat-containing wastewater through elastic polyurethane foam enables a significant reduction in the content of fats and suspended solids present in a coarse-dispersed state. In this case, the COD of the wastewater is reduced by more than twofold; however, it remains at a relatively high level, mainly due to organic components of blood.

Protein components of blood are present in the wastewater in a colloidal state. The particles of the dispersed phase of colloidal systems are electrically charged and surrounded by a hydration shell (i.e., they exhibit hydrophilic properties) and therefore cannot be removed by filtration through polyurethane foam. To remove these components together with emulsified fats, coagulation is applied.

According to literature data [14, 15], inorganic salts of polyvalent metals can be used for the chemical treatment of wastewater from meat-processing plants. Iron, aluminum, calcium, and magnesium salts are used as coagulants, as well as surfactants-catapin and catamine-which are salts of quaternary substituted ammonium and pyridinium compounds. Cationic surfactants are capable of changing the sign of negatively charged clay particles. It was assumed that, in our case, the positively charged catamine (or catapin) ion is capable of neutralizing the negative charge of emulsified fat particles and thus creating favorable conditions for emulsion breakdown.

As for polyvalent cations of inorganic salts, in water, they undergo hydrolysis, forming hydroxides with a highly branched floc structure capable of adsorbing colloidal and emulsified impurities from wastewater. Metal hydroxide micelles are positively charged, which promotes the destabilization of fat emulsions and enhances their coalescence and sorption onto metal hydroxide flocs. An analysis of domestic, foreign, and our own research results shows that ferric chloride is among the most effective coagulants for impurities in wastewater from the meat industry [11, 13–15, 17]. It is known [17] that proteins have a stabilizing effect on hydrophobic colloids formed during the hydrolysis of metal salts. In this regard, to enhance the coagulating effect and reduce the required coagulant dose, preliminary treatment of wastewater may be applied [28–29], including heating to a specific temperature; chlorination or treatment with other forms of "active" chlorine; and adjustment of pH to a specific value by acidification with diluted acid.

Experimental results showed that the temperature range for protein denaturation and coagulation in the investigated wastewater is 75–80 °C. When sodium hypochlorite is used as a source of active chlorine, the reagent dose required for destabilization of protein colloids is 20–25 mg/L, with a treatment (mixing) time of 0.5 h. The consumption of sulfuric acid (calculated as 98%) for destabilization of the colloidal system is 0.02 mL per 1L of wastewater. In this case, the pH of the wastewater decreased to 6.7, which corresponds to the isoelectric point and the point of zero charge of the colloidal solution of the hemoglobin protein [17], a component of blood.

As a result of preliminary treatment of the wastewater by one of the above methods, COD decreased by only 10–20%.

After destabilizing the protein colloids using one of the above methods, the wastewater was treated with ferric chloride. According to [13–15, 17], the consumption of coagulants (ferric chloride or aluminum sulfate) in the chemical treatment of fat-containing wastewater depends on the wastewater composition. It averages 100 mg (calculated as an anhydrous salt) per 1000 mg of pollutants determined by COD (at pH = 7). If the pH of the wastewater is below or above 7, the coagulant dose should be adjusted accordingly at a rate of 50 mg of reagent per unit change in pH. Considering that the COD of the investigated wastewater, which primarily determines coagulant consumption, varied over a wide range, jar tests were conducted across a broad COD interval.

Based on the jar test results, the ferric chloride dose for treating wastewater from the meat industry may range from 100 to 200 mg/L. For average wastewater or wastewater preliminarily treated by filtration through polyurethane foam media, a dose of 150 mg/L is recommended. The stability of the treatment effect for wastewater containing emulsified fats is observed when coagulation with ferric chloride is combined with flocculation using polyacrylamide (PAM). PAM promotes floc enlargement, with an optimal dose of 3–5 mg/L. The working concentration of the coagulant solution is selected depending on the type of dosing equipment and typically ranges from 5 to 10%. PAM is applied as a 1% solution. The flocculant is introduced into the treated water after coagulation, with an interval of up to 7 minutes [30].

Analyzing the presented data, it can be noted that the use of polyacrylamide (PAM), heating, chlorination, and pH adjustment has only a minor effect on improving treatment efficiency. These measures are mainly applied when it is necessary to stabilize the coagulation process, which can be identified during commissioning and start-up of treatment facilities. Subsequently, studies on the treatment of wastewater from the meat-processing industry were conducted using the following scheme: filtration through elastic polyurethane foam (EPUF), coagulation with sedimentation, and repeated filtration through EPUF.

Coagulated impurities were removed from the wastewater by sedimentation (fig.1).

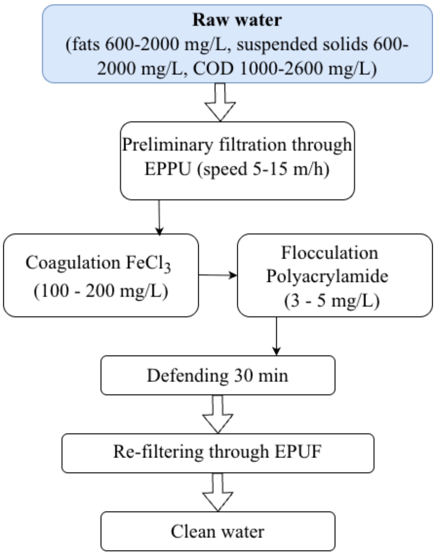

Figure 1: Two-stage technological scheme for treating fatty wastewater from the meat industry

As established, the central mass of coagulant flocs, together with the impurities adsorbed on them, settles within 10–15 minutes, while the remaining fraction settles after an additional 25–30 minutes. Based on this, two methods for separating impurities from water were investigated. The first involved sedimentation of reagent-treated water for 60–90 minutes (the time required for complete removal of flocs). The second involved passing the wastewater, after short-term sedimentation (20–30 minutes), during which the largest flocs fully settled, through a filtration column packed with polyurethane foam media.

The filtration time until regeneration of the EPUF packing was 16 hours for the first-stage filters and 18 hours for the second-stage filters (after coagulation and 30-minute sedimentation). The results of the studies conducted at a filtration rate of 5 m/h, a filter bed height of 2 m, and a packing density of 50 kg/m^3 are presented in Table 1.

Table 1. Comparative characteristics of wastewater quality before and after treatment

Indicator	Raw water	After treatment in EPPU	After filtration, coagulation and 1.5-hour sedimentation (Option I)	After filtration, coagulation, 0.5-hour sedimentation and repeated filtration through EPPU (Option II)
pH	7,4	7,4	6,7	6,7
COD, mg/L	2100	1560	790	630
BOD_{tot}, mg/L	1500	1040	560	470
Content, mg/L:				
fats and oils	1400	118	57	19
suspended solids	1600	290	101	54

As shown in the table, the wastewater treatment option based on the “filtration–coagulation–filtration” scheme yields higher performance. In this case, each of the wastewater pretreatment methods is effective and can be equally applied under practical conditions. About reagents, under industrial conditions, it is advisable to use technical ferric chloride with a concentration of 30 or 40% in accordance with TU 2152-004-00750907-2015 as the coagulant, and an aqueous sodium hypochlorite solution (“bleach”) containing up to 75% active chlorine. All working solutions were prepared at a concentration of 10%.

Thus, the developed wastewater treatment schemefiltration through EPUF, coagulation with 30-minute sedimentation, and repeated filtration through EPUF – enables the achievement of effluent quality that meets the requirements for discharge into a municipal sewerage system. The raw wastewater had the following characteristics: pH = 7.4; COD = 2100 mg/L; total BOD = 1500 mg/L; fat content = 1400 mg/L; and suspended solids = 1600 mg/L. After treatment by EPUF filtration, the pH remained unchanged, while the other parameters decreased to the following values: COD = 1560 mg/L; total BOD = 1040 mg/L; fats = 118 mg/L; and suspended solids = 290 mg/L.

After filtration, coagulation, and 1.5 hours of sedimentation, the treated wastewater exhibited a decrease in pH from 7.4 to 6.7; COD was 790 mg/L; total BOD was 560 mg/L; fat content was 57 mg/L; and suspended solids were 101 mg/L. Following EPUF filtration, coagulation, 30-minute sedimentation, and repeated filtration through EPUF, the treated water exhibited the following characteristics: pH = 6.7, COD = 630 mg/L, total BOD = 470 mg/L, fat content = 19 mg/L, and suspended solids = 54 mg/L. At the same time, the total nitrogen concentration decreased from 15–186 to 14–47 mg/L, and phosphorus from 12–59 to 3–9 mg/L. Thus, the quality of the treated water meets the requirements for discharge into a municipal sewerage system.

Additionally, the impact of initial pollutant concentrations on the increase in head loss within the filter bed, treatment efficiency, and filtration duration was examined. A study examining the impact of fat and suspended solids concentrations in the influent water – typical of wastewater from the meat-processing industry – on treatment efficiency and head loss increase at filtration rates of 5–15 m/h yielded the following results.

With increasing suspended solids content in the influent water, the rate of head loss increase rose, leading to a reduction in filtration duration.

An analysis of head loss dynamics revealed that at a filtration rate of 5 m/h and a packing density of 50 kg/m^3, the head loss increased by 0.3-1.0 m/h at influent fat and suspended solids concentrations ranging from 600 to 2000 mg/L. At a filtration rate of 15 m/h, packing density of 50 kg/m^3, and a filter bed height of 2 m, the head loss increase ranged from 0.5 to 1.6 m/h. The pressure loss by the end of the filtration cycle reached 9.5 m, which is consistent with the results of our previous studies [24].

The results of investigations into the influence of fat and suspended solids concentrations on treatment efficiency and filtration duration using the "filtration–coagulation–filtration" scheme are presented in Table 2.

Table 2. Results of research on the treatment of wastewater containing fats from the meat industry

Test No.	Filtration rate (V_f), m/h	Impurity concentration in treated water, mg/L			Impurity concentration after treatment, mg/L			Filtration duration (T_f), h
		fats(C_f)	suspended solids ($C_{s.s}$)	COD(C_{COD})	fats (C_f)	suspended solids ($C_{s.s}$)	COD ($C_{COD\text{-after treatment}}$)	
1	5	600	2000	2600	14	68	690	18
2	5	2000	600	2600	17	23	660	19
3	15	600	600	2600	14	27	780	21
4	15	2000	2000	2600	40	118	895	7
5	5	600	600	1000	9	14	305	36
6	5	2000	2000	1000	29	80	440	11
7	15	600	2000	1000	16	94	410	9
8	15	2000	600	1000	19	34	480	10

From the presented data obtained under the established boundary conditions (Table 2), it can be seen that the removal efficiency for fats ranges from 97.3–99.1%, for suspended solids from 94.1–96.6%, and for COD from 52.0–74.6%. An increase in the filtration rate (Vf) led to a deterioration in the quality of the filtered water and, consequently, to a reduction in the filtration duration or filtration cycle (Tf).

The planning and processing of experimental results were carried out using standard methodologies based on the least squares method [31–32]. Based on the experimental data and calculation results, the homogeneity of variances was verified using Cochran's test, the reproducibility variance was determined, the regression equation coefficients were obtained, the adequacy of the equations was assessed, and statistically insignificant coefficients were eliminated.

Additional experiments with EPP filters demonstrate that optimising the loading layer height (1.5-2.5 m) and filtration rate can increase the cycle time by 20-30%, with COD removal efficiency of up to 80% in combination with coagulation [35].

The significant input experimental parameters are [24, 26]:

- Filtration rate, Vf, m/h (X_1). Variation range: 5–15 m/h (average value: 10 m/h);
- Fat concentration in influent water, Cf, mg/L (X_2). Variation range: 600–2000 mg/L (average value: 1300 mg/L);
- Suspended solids concentration in influent water, Css, mg/L (X_3). Variation range: 600–2000 mg/L (average value: 1300 mg/L);
- COD value of influent water, CCOD, mg/L (X_4). Variation range: 1000–2600 mg/L (average value: 1800 mg/L).

According to the number of selected factors, the corresponding regression equation has the following form [31–32]:

$$Y = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + \\ + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (1)$$

where b_j are the estimated regression coefficients;

x_i are factors;

Y is the response function.

The coefficient b_0 is the arithmetic mean value of the response (intercept); b_1, b_2, b_3, b_4, haracterize the relative significance of each term (linear terms); b_{12}, b_{13}, b_{23} evaluate the mutual influence of each pair of factors (two-factor interaction). The factors x_i are defined as the ratio of the difference between the input value (X_j) and the average value (X_{0j}) of the corresponding parameter (X_1...X_4) to the variation intervalΔX_j:

$$x_i = \frac{\left(X_j - X_{0j}\right)}{\Delta X_j} \quad (2)$$

The response functions were defined as the fat content in the treated water, $C_{f(after\ tr.)}$, suspended solids concentration, $C_{s.s.(after\ tr.)}$, COD, $C_{COD(after\ tr.)}$ and filtration duration (T_f) (Table 3).

Table 3. Numerical values of regression coefficients in response functions after treatment

Estimated regression coefficients	Response function			
	C_f	$C_{s.s.}$	C_{COD}	T_f
b_0	19,75	57,25	582,5	16,375
b_1	2,5	11,0	58,75	–4,625
b_2	6,5	6,5	36,25	–4,625
b_3	5,0	32,75	26,25	–5,125
b_4	1,5	1,75	173,75	–0,125
b_{12}	0,75	1,25	10,0	1,375
b_{13}	0,75	5,0	–15,0	1,375
b_{23}	3,25	2,5	22,5	2,375

The absolute values of the obtained coefficients indicate the degree of influence of each factor on the output parameters of the process.

It was established that the concentrations of fats and suspended solids in the treated water are mainly affected by their initial concentrations. The only controllable parameter, the filtration rate, has a relatively moderate effect on the concentrations of fats and suspended solids, whereas the influence of Vf on the COD value at the outlet is significantly greater The filtration duration is influenced by all four factors: the filtration rate and the concentrations of fats and suspended solids have the strongest effect, while the COD value of the influent water has a lesser impact.

The above data (dependencies (1) and (2), Table 3), after generalization and transformation, made it possible to obtain final relationships for practical calculations under real operating conditions:

$$C_{f(after\ tr.)} = 6,798 - 0,571V_f - 0,00148C_{f(effluent)} - 0,00362C_{s.s.(effluent)} + 0,00187C_{COD(effluent)} + 0,000214V_f\,C_{f(effluent)} + 0,000214V_f\,C_{s.s.(effluent)} + 0,0000066C_{f(effluent)}\,C_{s.s.(effluent)} \quad (3)$$

$$C_{s.s(after\ tr.)} = -9,744 - 0,121V_f - 0,000918C_{f(effluent)} - 0,029C_{s.s.(effluent)} + 0,00218C_{COD(effluent)} + 0,000357V_f\,C_{f(effluent)} + 0,00143V_f\,C_{s.s.(effluent)} + 0,0000051C_{f(effluent)}\,C_{s.s.(effluent)} \quad (4)$$

$$C_{COD(after\ tr.)} = 17,0217 - 13,607V_f - 0,036C_{f(effluent)} - 0,0207C_{s.s.(effluent)} + 0,217C_{COD(effluent)} + 0,00286V_f\,C_{f(effluent)} + 0,00429V_f\,C_{s.s.(effluent)} + 0,0000459C_{f(effluent)}\,C_{s.s.(effluent)} \quad (5)$$

$$T_f = 62,419 - 1,946V_f - 0,0168C_{f(effluent)} - 0,0175C_{s.s.(effluent)} + 0,000156C_{COD(effluent)} + 0,000393V_f\,C_{f(effluent)} + 0,00429V_f\,C_{s.s.(effluent)} + 0,0000048C_{f(effluent)}\,C_{s.s.(effluent)} \quad (6)$$

The obtained results (dependencies (3–6)) make it possible, under the accepted boundary conditions, to determine the required filtration cycle duration and the levels of contaminant concentrations in the treated water. The significance of the coefficients was determined by constructing confidence intervals.

4. Conclusions

As a result of generalizing the experience in treating wastewater from the meat-processing industry and conducting a comprehensive set of experimental studies [24–27], the authors proposed and scientifically substantiated a scheme for local treatment of such effluents.

The scheme provides for preliminary filtration of wastewater using pressure filters filled with elastic polyurethane foam, coagulation with ferric chloride at a dose of 100–200 mg/L, treatment with sodium hypochlorite, 30-minute sedimentation, and secondary filtration through EPPU filters.

The boundary conditions adopted in the experiments correspond to real operational data of existing treatment facilities for fat-containing wastewater, namely: initial concentrations of suspended solids and fats of 600–2000 mg/L, and COD of 1000–2600 mg/L.

The main influencing factors (influent water quality and filtration rate) were identified, and their mutual interactions were evaluated. A statistical–probabilistic mathematical model was developed to determine the key parameters of the wastewater treatment process by filtration through EPPU.

Based on the experimental data, regression equations in coded and real variables (3–6) were obtained, allowing the determination of the technological parameters of wastewater treatment.

Implementation of the wastewater treatment scheme proposed by the authors for the meat-processing industry will ensure a reliable and sufficient treatment efficiency for the discharge of treated wastewater into the municipal sewerage system.

The proposed technology not only achieves high treatment efficiency and compactness but also offers strong potential for mechatronic implementation. By integrating sensors, controllers, and actuators, the system can achieve automated adaptive control – for example, dynamically adjusting filtration rate or coagulant dose in response to real-time influent quality variations. This mechatronic approach enhances reliability, reduces operational costs, and supports sustainable wastewater management in the meat-processing sector.

References

[1] Latiffi, N. A., Saphira, R. M., & Shanmugan, V. A. (2019) Characteristics of Water Quality from Meat Processing Wastewater. Journal of Advanced Research in Applied Sciences and Engineering Technology, 1(17), 78-84.

[2] Aleksić, N., Nešović, A., & Šušteršič, V. (2020). Slaughterhouse water consumption and wastewater characteristics in the meat processing industry in Serbia. Desalination and Water Treatment, 190, 98-112. https://doi.org/10.5004/dwt.2020.25745

[3] Zanol, M. B., Pereira Lima, J. P., & Assemany P., (2024). Assessment of characteristics and treatment processes of wastewater from slaughterhouses in the state of Minas Gerais, Brazil. Journal of Environmental Management, 358. https://doi.org/10.1016/j.jenvman.2024.120862

[4] Nugroho, F.A., Arif, A.Z., & Sabila, G.Z. (2021). Slaughterhouse Wastewater Treatment by Electrocoagulation Process. IOP Conference Series: Materials Science and Engineering, 1115. https://doi.org/10.1088/1757-899X/1115/1/012037

[5] Enterprises of the meat processing industry (2024). Retrieved from https://ecbit.com.ua/predpriyatiya-myasopererabatyvayushchey-promyshlennosti (in Ukr.).

[6] Rules for accepting wastewater into centralized drainage systems (2023, December). Order of the Ministry of Community Development, Territories and Infrastructure. URL: https://zakon.rada.gov.ua/laws/show/z0056-18#Text

[7] Rouland, G., Safferman, S. I., & Schweihofer, J. P. (2024). Characterization of Low-Volume Meat Processing Wastewater and Impact of Facility Factors. Water, 16(4). https://doi.org/10.3390/w16040540

[8] Kovalchuk, V.A. (2002). Sewage treatment. Rivne: VAT Rivnenska drukarnya (in Ukr.).

[9] Epoyan, S.M. & Lukashenko, S.V. (2020, May 13-14). Application of elastic polyurethane foam for intensification of cleaning of fat-containing wastewater of the meat industry. Abstracts of reports. 75 scientific and technical conference of KhNUBA, 82 – 83.

[10] Petruk, V.G., Severin, L.I., Vasilkivskiy, I.V., & Bezvovnuk, I.I. (2016). Environmental technologies. Study guide. Part 2: Wastewater treatment methods. Vinnitsa: VNTU (in Ukr.).

[11] Kovalchuk V.A. (2015). Animal husbandry and meat processing: modern methods of wastewater treatment. Vistik Odeskoi derzhavnoi akademii budivnitsnva ta architekturi [Bulletin of the Odessa State Academy of Construction and Architecture], 59, 194-199 (in Ukr.).

[12] Electrochemical treatment of wastewater (2024). Retrieved from https://stud.com.ua/462/ekologiya/elektrohimichna_ochistka_stichnih#goog_rewarded (in Ukr.).

[13] Kovalchuk V.A. (2010). Complex technology of wastewater treatment of the meat processing industry. World Meat Technologies, 11, 71-75 (in Ukr.).

[14] Savchuk, L., Znak, Z., Kurylets, O., & Mnykh, R. (2017). Research into processes of wastewater treatment at plants of meat processing industry by flotation and coagulation. Eastern-European Journal of Enterprise Technologies, 33(10(87)), 4–9. https://doi.org/10.15587/1729-4061.2017.101736

[15] Uglyar, Yu. M., Borshchyshyn, I. D., & Khromyak, U. V. (2014). Electroflotocoagulation wastewater treatment of LLC «Kolomyia meat-processing plant». Eastern-European Journal of Enterprise Technologies, 2, 30-34. https://doi.org/10.15587/1729-4061.2014.22986

[16] Kovalchuk, V.A. (2011.) Development of scientific and practical principles of intensification of the work of facilities for flotation and biological treatment of wastewater of meat processing enterprises. Abstract of thesis doctoral dissertation. Rivne: NUVGP (in Ukr.).

[17] Hirol, M.M., Hirol, A.M., & Hirol, A.M. (2013). Industrial wastewater treatment technologies. Rivne: NUVGP (in Ukr.).

[18] Gasiunas, V. (2015). Efficiency of ferric sulphate for removal of phosphorus from meat processing wastewater. Proceedings of the 7th International Scientific Conference Rural Development, 1-5. https://doi.org/10.15544/rd.2015.077.

[19] Amuda, O., Alade, A. (2006). Coagulation/flocculation process in the treatment of abattoir wastewater. Desalination. 196(1–3), 22–31. https://doi.org/10.1016/j.desal.2005.10.039.

[20] Jachimowicz, P., Cydzik-Kwiatkowska, A., & Szklarz Jachimowicz, P. (2020) Effect of Aeration Mode on Microbial Structureand Efficiency of Treatment of TSS-Rich Wastewater from Meat Processing. Applied Sciences. 10(21). https://doi.org/10.3390/app10217414.

[21] Mutua, D. N., Mwaniki Njagi, E. N., & Orinda, G. (2016). Biological Treatment of Meat Processing Wastewater Using Lab-Scale Anaerobic-Aerobic/Anoxic Sequencing Batch Reactors Operated in Series. Journal of Bioremediation & Biodegradation, 7(4). https://doi.org/10.4172/2155-6199.1000362

[22] Kimura, A., Kubo, M. (2006). Fats and Oils-Containing Wastewater Treatment with Fats and Oils-Degrading Microorganisms. Oleoscience, 6(10), 501-506. https://doi.org/10.5650/oleoscience.6.501

[23] Abyar, H., Nowrouzi, M. (2020). Highly Efficient Reclamation of Meat-Processing Wastewater by Aerobic Hybrid Membrane Bioreactor-Reverse Osmosis Simulated System: A Comprehensive Economic and Environmental Study. ACS Sustainable Chemistry & Engineering, 8(37), 207–216. https://doi.org/10.1021/acssuschemeng.0c05298

[24] Lukashenko, S., Syrovatskyy, O., & Karahiaur, A. (2025b). Application of elastic foampolyurethane for the treatment of meat industry wastewater. Municipal Economy of Cities, 1(189), 243–251. https://doi.org/10.33042/2522-1809-2025-1-189-243-251.

[25] Lukashenko, S., Syrovatskyy, O., Karahiaur, A. & O. Haiduchok (2025, April 22-25). Enhancing the treatment efficiency of fat-containing wastewater using elastic polyurethane foam filters. The 16th International scientific and practical conference "Innovative development models: trends and innovations". Athens, Greece, 151-154. https://doi.org/10.46299/isg.2025.1.16.

[26] Lukashenko, S. & Syrovatskyy, O. (2025, June 11-12). Wastewater treatment of the meat industry by filtration through elastic polyurethane foam. Materials of the International Scientific Internet Conference "Information Society: Technological, Economic and Technical Aspects of Formation". Opolu, Poland, 87-91. http://www.konferenciaonline.org.ua/ua/article/id-2235/.

[27] Lukashenko, S., Syrovatskyy, O., Haiduchok, O., & Titov, A. (2025). Study of the mechanism of sorption of fats by polyurethane foam frommeat and dairy industry wastewater. Municipal Economy of Cities, 4(192), 250–257. https://doi.org/10.33042/3083-6727-2025-4-192-250-257

[28] Gągol, M., Przyjazny, A., & Boczkaj, G. (2018). Wastewater treatment by means of advanced oxidation processes based on cavitation – A review. Chemical Engineering Journal, 338, 599–627. https://doi.org/10.1016/j.cej.2018.01.049.

[29] Vashkurak, U., Shevchuk, L., Nykulyshyn, I., & Aftanaziv, I. (2018). Research into effectiveness of cavitation cleaning of wastewater of a fatandoil plant from organic and biological contamination in the presence of various gases. Eastern-European Journal of Enterprise Technologies, 3(10 (93), 51–58. https://doi.org/10.15587/1729-4061.2018.131953

[30] Syrovatskyy, O., Karahiaur, A. (2024). The research of sedimentation properties of particles in neutralized industrial wastewater. Scientific Bulletin of Construction, 111, 105-112. https://doi.org/10.33042/2311-7257.2024.111.1.14

[31] Volokita, A.M., Selivanov, V.L. (2022) Fundamentals of the theory of experimental design. Igor Sikorsky Kyiv Polytechnic Institute (in Ukr.).

[32] Paraska, G.B., Pribega, D.V., & Maidan P.S. (2017) Methods and means of experimental research. Kyiv: Kondor, (in Ukr.).

[33] Shkop, A., Trembitskyi, D., Shestopalov, O., Bosiuk, A., Loboiko, V., Sakun, A., Ponomarova, N., & Petrescu, Ligia-Luminița. (2025). Study of the process of mechanical dewatering of liquid waste from municipal wastewater treatment plants in sedimentation centrifuges. International Journal of Mechatronics and Applied Mechanics, 1(20), 366-375. https://doi.org/10.17683/ijomam/issue20.38

[34] Shkop, A., Ponomarova, N., Shestopalov, O., Bosiuk, A., Sakun, A., Romanchyk, A., & Matiss, D. (2025). Investigation of the feasibility of micelle separation in bone meal production using a sedimenting centrifuge. International Journal of Mechatronics and Applied Mechanics, I(21), 420-428. https://doi.org/10.17683/ijomam/issue21.39

[35] Karahiaur, A., Haiduchok, O., Syrovatskyy, O., Titov, A., Shestopalov, O., Shkop, A., Bosiuk, A., & Petrescu, Ligia-Luminița. (2025). Reused fabrics in three-layer filters: performance and modeling. International Journal of Mechatronics and Applied Mechanics, I and II(22), 60-66. https://doi.org/10.17683/ijomam/issue22.v1.6