Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.25778

199 (2020) 205–211
September

Removal of total petroleum hydrocarbons from wastewater and sewage sludge generated in oil separators and evaluation of the process efficiency

Anna Grobelak*, Małgorzata Worwąg, Anna Grosser

Czestochowa University of Technology, Faculty of Infrastructure and Engineering, Czestochowa, Poland, emails: anna.grobelak@pcz.pl (A. Grobelak), mworwag@is.pcz.czest.pl (M. Worwag), agrossser@is.pcz.czest.pl (A. Grosser)

Received 5 December 2019; Accepted 27 February 2020

ABSTRACT

The paper presents the results of research on the removal of total petroleum hydrocarbons (TPHs), (initial content of petrol (C6–C12) 1,558.77 mg/L, and oil (C12–C35) 7,426.61 mg/L) in wastewater from oil separators using biological as well as physical and chemical methods. The ratio of removal of petroleum compounds was compared in the used methods, analyzing the sum of petrol and oil. Studies using biological methods have been conducted for three bacterial strains: *Pseudomonas putida, Bacillus subtilis* and *Azospirillum brasilense* immobilized on sodium alginate and biochar. In the case of physical and chemical methods the following chemical oxidation and coagulation processes were used: iron(III) chloride and aluminum sulfate in dose from 50 to 275 mg/L of the tested sample. The biological treatment applied for 6 weeks confirmed 97%–98% removal of TPHs, indicating the highest removal rate for *Azospirillum brasilense* treatment. It was found that the highest TPHs removal efficiency (99%) of both petrol and oil in wastewater was achieved when Fenton's reaction was applied, during a few hours of treatment. This reaction can, therefore, be an effective tool in removing TPHs from sludge and wastewater from oil derivative separators. The results of the conducted tests confirm that it is possible to almost completely remove petroleum substances in wastewater and sludge from oil separators using hybrid methods combining biological, chemical, and physical treatment. In the aspect of current trends the most preferable method shall be biological, without secondary residues generation, but this process requires much more time.

Keywords: Total petroleum hydrocarbons; Oil separators; Coagulation; Biochar; Bioremediation

1. Introduction

The crude oil is the crucial element of the energy and chemical industries, thus the petroleum contaminants are becoming more widespread. Contamination of the environment with the total petroleum hydrocarbons (TPHs) is currently increasing and their migration in the environment causes many threats. The negative impact of petroleum substances on the soil and water environment as well as on animals, plants, and people is confirmed. One of the preventive tools is the use of petroleum-derived separators collecting oily wastewater from hardened anthropogenic surfaces, protecting against soil and water environment contamination. Petroleum compounds in the soil environment affect biotic components (humans, plants, and animals) and abiotic components [1], undergoing a variety of processes such as physical abiotic processes, chemical, and biological changes, interactions with microorganisms and weathering [2]. In the environment, these substances can be in the form of hydrocarbons dissolved in water, vapors, or can be absorbed in soil particles. Petroleum substances can be accumulated in organisms, which results in metabolic disorders. Through the food chain, these contaminants can reach humans, exposing them to mutagenic changes or

* Corresponding author.

Presented at the 14th Conference on Microcontaminants in Human Environment, 4–6 September 2019, Czestochowa, Poland

1944-3994/1944-3986

increasing the risk of cancer [1]. TPHs release into the environment is a potential health risk. These substances have been reported to leak into groundwater. The problem of oil-based pollution is most affecting urban agglomerations and industrialized areas [3]. Petroleum compounds are flushed from the catchment and get with rainwater through surface drainage to surface waters. In addition, wastewater from rainfall from refineries and petrochemical plants is characterized by high oil content in the range of 50–2,000 mg/L [4]. Therefore, pre-treatment of wastewater originating from for example, roads, parking areas, vehicle dismantling stations, and car workshops seems to be required before the final disposal in wastewater treatment plants. Thus the simple and efficient methods of TPHs contaminated wastewater treatment are required. Due to the diversity of petroleum sludge, chemical, physical, and biological methods are used to remove toxic TPHs from the wastewater. Biological methods rely on the use of metabolic pathways and cycles of interacting microorganisms to remove contaminates or transform them into forms that are less harmful [5]. Currently, for water treatment, the most effective methods are membrane technologies, like microfiltration membrane (MF), ultrafiltration membrane (UF), nanofiltration membrane (NF), reverse osmosis (RO), forward osmosis (FO) [6], but these methods are used mostly for water treatment. Another method uses for water and wastewater treatments is granular filtration, which unfortunately generates large amounts of secondary wastes, and flocculation, which requires significant energy input [7]. Coagulation is the alignment of the two processes, as cohesion allowing colloidal particles to aggregate and flocculation causing colloidal units to coalesce by adsorption of high molecular substances [7]. At current, coagulation is the most common practice used in water and wastewater treatment. Many scientists make an effort to connect coagulation and flocculation with other methods, to increase the effectiveness of water treatment [8]. In the research of Piekutin (2018) the removal of petroleum compounds from distilled water enriched with a mixture of diesel fuel and gasoline using a combination of coagulation and reverse osmosis were applied [8]. At present, also chemical methods, primarily oxidation, are used to remove petroleum compounds. During this process, petroleum compounds can be transformed into more easily degradable or mineralized forms. The process involves the reaction of chemical oxidants with organic contaminants in the sludge or wastewater, causing the subsequent transformation, destruction, and conversion of the contaminants into non-hazardous, stable, less mobile, and inert compounds that may undergo further treatments [5]. It is an alternative to biological or physical methods and an important auxiliary factor for natural pollution-reducing processes. The effectiveness of chemical methods depends on the oxidizer used, the properties of contaminants, pH, and temperature. Oxidation can remove, among others, TCE (trichloroethylene), PCE (eticyclidine), PAH (polycyclic aromatic hydrocarbons), BTEX (benzene, toluene, ethylbenzene, and xylene), phenols, ketones, aldehydes, and alcohols. The final oxidation of organic contaminants will lead to creating carbon dioxide (CO_2), water (H_2O), and inorganic chlorides [5]. The most commonly used oxidants are ozone, hydrogen peroxide, potassium permanganate, and chlorine compounds. To increase the efficiency of the process using hydrogen peroxide, reactions with Fe^{2+} ions, ozone, or the use of ultraviolet radiation are often applied. The efficiency of the process can be increased by using reactive mainly hydroxyl $OH^{\bullet}$ radicals [9]. The results of the TPHs removal confirm a much higher degree of reduction of the tested compounds for the Fenton's reaction compared to the use of only hydrogen peroxide as an oxidant [9], similar results were found for PAHs removal [8]. Moreover, ultrasound-assisted treatment is also used for organics removal [9]. Coagulation is also a commonly used process to remove petroleum compounds [8], where aluminum sulfate and ferric chloride is often applied for the process. However, pre-hydrolyzed coagulants are increasingly used. They have hydroxyl groups, which is why they have increased alkalinity. Among them the polyaluminum chlorides are most widely used [4]. The effectively combined coagulation with powdered activated carbon (PAC) was applied to remove benzo (a) pyrene and 16 PAHs from surface water [10]. Bioremediation methods for removing oil contaminants from soil and sludge are becoming more and more popular due to the zero waste nature of these methods. Unfortunately, the properties of the environment and its conditions largely determine the possibility of using bioremediation at the site of contamination (in situ), because they affect microbiological activity (e.g. humidity, temperature), or the transport of contaminants to microorganism cells (e.g. quality and content of organic matter [11]. Currently, hydrocarbons present in the environment are being biologically degraded primarily by bacteria and fungi. Moreover, the bacteria used in the bioremediation should be characterized by high efficient biodegradation rate and nonpathogenic or virulence properties. Mostly genera of *Pseudomonas, Burkholderia, Enterobacter, Acinetobacter, Gordonia, Mycobacterium, Micrococcus, Nocardioides, Rhodococcus, Pseudomonas,* and *Rahnella* represents a majority of autohtoninic microbial population from petroleum contamination environments [12,13]. In the literature some bacteria strains have been described to remove the hydrocarbons with high efficiency from the environment: *Escherichia* sp. strain UIWRF0110, *Chryseobacterium* sp. strain AJ0 [14]. The bacteria involved in the decomposition of petroleum compounds use them as a source of the necessary carbon and transform into energy. The most common method of aerobic degradation of n-alkanes is terminal oxidation with the participation of monooxygenases. The condition for the correct course of this process is the availability of *C* to the organic catalytic efficiency of enzymes contained in cells or induced towards substrates. Microorganisms used to break down petroleum compounds have specific genes like *catA, bphA, ndoB, xylE, alkB,* or *todC*, which code for enzymes responsible for TPHs biodegradation [15]. Petroleum hydrocarbons are mainly degraded by enzymatic mechanisms, attachment, and binding of microbial cells to the substrates, the synthesis of biosurfactants, and emulsifiers [16].

Currently, waste amounts from oil separators are increasing, in the form of sludge and oily wastewater. This phenomenon results from the regulation of requirements regarding the discharge of rainwater from paved areas such as parking or storage halls [17]. Unfortunately, the number of services offered to the market in this area does not increase sufficiently, mainly due to complicated low regulations. Very often, such wastewater and sludge from separators are most often collected and mixed with municipal wastewater at the wastewater treatment plants. This is due to the insufficient number of technology implementations for the treatment of this type of wastewater and sludge containing TPHs.

Therefore, for this reason simple and cheap technologies are needed to make such waste being easily and effectively neutralized. The conducted study was aimed at determining the effectiveness of wastewater treatment collected from oil separators. In this study three methods were analyzed: biological degradation using bacteria, chemical oxidation, and coagulation/flocculation. Moreover the determination of the most effective dose of reagents and selection of the appropriate species of bacteria were tested.

2. Materials and methods

2.1. Characteristics of research substrates

The substrate for the study were wasted from oil separators (coalescence separator) from the storage hall of a transport company (Poland). The investigated sludge from the oil separator is a complex mixture of petroleum hydrocarbons, water, and sediments. The amounts of 20 L of wastewater and sewage sludge mixture was collected from the operating separator. Then the mixture was homogenized using blender for further analysis. According to the waste catalogs these substances are classified as hazardous waste and identified as wastewaters and sludge from oil separators. The analysis of the basic physical parameters as pH (direct measurement using potentiometric method; 7.77–7.74) and chemical parameters: total nitrogen content (N) by Kjeldahl method (952.0–1150.0 mg/L), phosphorus (P) content by spectrophotometric method after complete digestion (14.5–27.2 mg/L) of the tested materials were carried out according to standard procedures as describes previously [18].

The concentration of petrol and oil was determined using the Thermo Scientific (Germany) GC–FID system, equipped with Rxi®-5ms column (fused silica) and FID detector (injector 2500C,). The split injection mode was used. Helium was used as a carrier at a flow rate of 3 mL/min. The injection volume was 1 μL. The initial temperature was 70°C and was heated to a final temperature of 300°C at a constant rate of 10°C/min. The total concentration of each of the analytes (petrol and oil) was determined from the corresponding calibration curve. Known concentrations of a mixture of petrol and oil suspended in hexane were directly injected into the gas chromatograph. Each calibration curve was performed with seven different concentrations in triplicate. Curves were linear for the concentration range 25–25,000 mg/L for each analyte (coefficient of determination were equal to 0.998 and 0.996 for petrol and oil, respectively). The detection limit of detection (LOD) and quantification limits limit of quantification (LOQ) of the method were 37 mg/L for petrol, 75 mg/L for oil, and 112 mg/L for petrol and 201 mg/L for oil, respectively.

2.2. Extraction procedure

The following reagents were used in the tests: (i) 7.5 mL hexane and 2.5 mL dichloromethane (1: 3 ratio) and (ii) before injection: filtering samples using a 0.45 μm PTFE syringe filter, conditioning of columns (2.5 mL of hexane for columns, Florosil filling), filtering the samples through a Florosil filter, transfer of the filtered samples into chromatographic vials (0.75 mL) for TPHs determination (petroleum C6–C112 and oil C12–C35).

2.3. Statistical analysis

For methods A, B, and C, a two-way analysis of variance (ANOVA) was carried out to determine the effect of method and dose of coagulants on the concentration of petrol and oil in the sample as well as their removal. While in the case of methods D and E one-way ANOVA was made to determine whether the dose or type of microbial consortium affects the mentioned indicators. In the case of statistically significant between data a post hoc was made (Tukey honest significant difference (HSD)). The statistical analyzes were carried out using STATISTICA (STATISTICA 8.0). The one way ANOVA test was done with at least three replications. The homogeneity of variances was checked using Levene's test. Data that failed the ANOVA assumptions were analyzed via the Kruskal–Wallis test.

2.4. Treatments methods

An overall experimental scheme is included in Fig. 1.

2.4.1. Treatment using biological agents

The biological method using microorganisms was used to decompose petroleum-derived compounds (TPHs). For this purpose, alginate capsules were created based on microorganisms decomposing petroleum compounds – *Bacillus subtilis, Azospirillum brasilense, Pseudomonas putida.* Microorganisms have been immobilized in biochar and alginate as previously described [11]. Ultimately, for every 30 g of microbiological preparation obtained, 5 g of biochar and 25 g of alginate consisted of and the number of bacterial cells was (10^9–10^{11} per g). The 300 ml of contaminated oily substances were poured into glass bottles and 30 g of alginate capsules were added to investigate the efficiency of bacterial bioremediation for 6 weeks according to the scheme (Fig. 1). The mixtures prepared in this way were tested on a Micro-Oxymax respirometer (Columbus) and measured for CO_2 generation, which is the final product of the total metabolism of petroleum compounds by bacteria.

2.4.2. Oxidation

Another solution to remove TPHs was the oxidation using Fenton's reaction. The following reagents were used in the tests: iron(II) sulfate $FeSO_4$ $7H_2O$, hydrogen peroxide H_2O_2. The petroleum-contaminated wastewaters (300 ml) were poured into 1000 ml conical flasks. Then, iron(II) sulfate and hydrogen peroxide were applied in different ratios as shown in Fig. 1 and the mixing were applied for 120 min (200 rpm) following the sedimentation for 120 min. To summarize, the treatment was divided into three different phases: coagulation, flocculation, and sedimentation. After the procedures were carried out, the tested material was

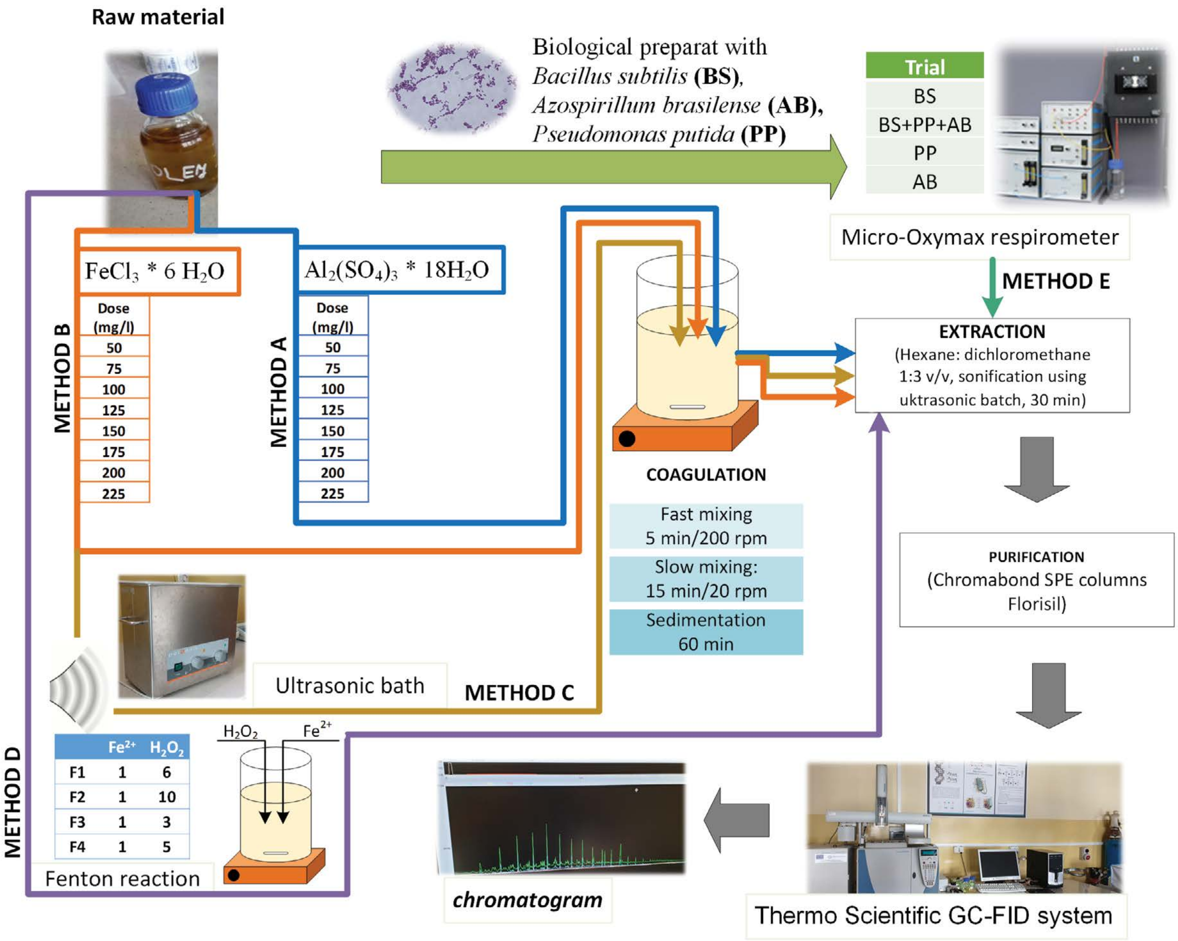

Fig. 1. Experimental overview scheme.

subjected to chromatographic analysis to assess the degree of TPHs removal.

2.4.3. Coagulation

To remove and separate petroleum compounds, coagulation was applied using two reagents (aluminum sulfate(VI) $Al_2(SO_4)_3 \cdot 18H_2O$ and iron(III) chloride $FeCl_3 \cdot 6H_2O$) (Fig. 1). In addition, ultrasound treatment was used in one of the series of tests (10 min and 50 Hz). The following parameters of the coagulation process were used: fast mixing time of 5 min at 200 rpm, 15 min slow mixing time at 20 rpm, 60 min sedimentation time.

3. Results and discussion

3.1. Biological treatment

Measurements of CO_2 produced in the Micro-Oxymax respirometer during biological treatment (data not shown) with microorganisms indicated a steady tendency in the increase of carbon dioxide emissions up to the second week of measurements (max 0.5–0.8 mg/L), the next 7 d were characterized by a significant decrease in the produced content of CO_2 (up to 0.0714 mg/L). From the fourth week, stabilization of measurements (0.03–0.02 mg/dm^3) was observed until the end of the experiment in the last sixth week of measurement. No statistically significant differences in the results between the applied microorganism treatments were noted $F = 1.23$, $p = 0.13$, (Fig. 2) while for the control without microorganisms, the CO_2 production was 40%–60% lower for the compared measurement periods. For microbial treatment the chromatographic analysis of petrol and oil confirmed over 90% degree of TPHs removal compared to controls after six weeks of experiment (Fig. 2). Zacharyasz et al. [19] also found an increased number of *Pseudomonas* sp. and *Bacillus* sp. bacteria in TPHs contaminated water, indicating the biodegradation properties by these bacteria species and adaptation properties. In the investigated research the most effective in TPHs bioremediation and also commonly found representatives genera of *Pseudomonas* and *Bacillus* were also used [13]. Grobelak et al. [17] also noted that the petroleum hydrocarbon-degrading consortium characterization indicated the dominance of bacteria assigned to *Pseudomonas* sp., *Comamonas* sp. and *Ochrobactrum* sp. Dombrowski et al. [20] confirmed that the remediation of petroleum hydrocarbon contamination requires the mutual action of multiple functional bacteria to

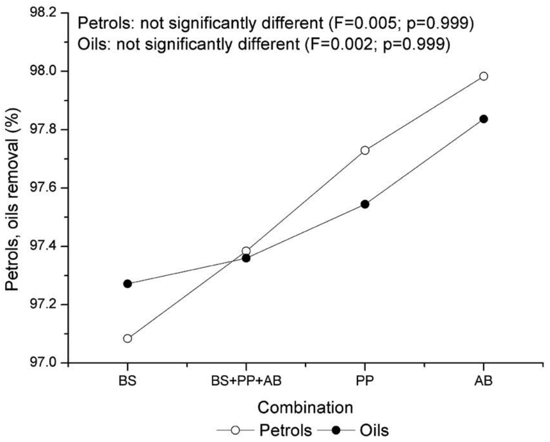

Fig. 2. TPHs (petrol and oil) removal during biological treatment calculated in comparison to control; BS – *Bacillus subtilis*, BS+PP+AB – *Bacillus subtilis, Azospirillum brasilense, Pseudomonas putida*, PP – *Pseudomonas putida*, AB – *Azospirillum brasilense.*

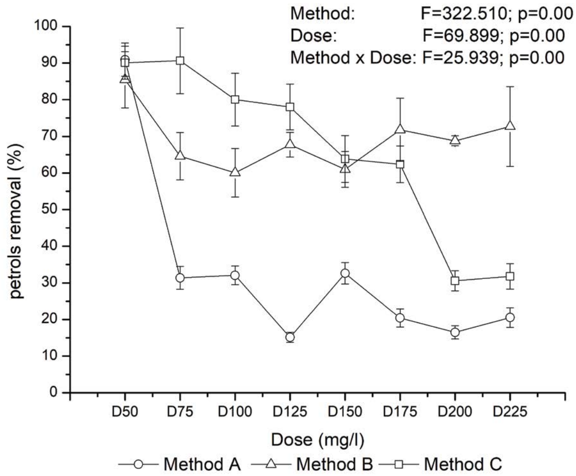

Fig. 3. Petrol (C6–C12) removal percentage efficiency using the coagulation; A – aluminum sulfate(VI), B – iron(III) chloride, C – ultrasounds, and iron(III) chloride.

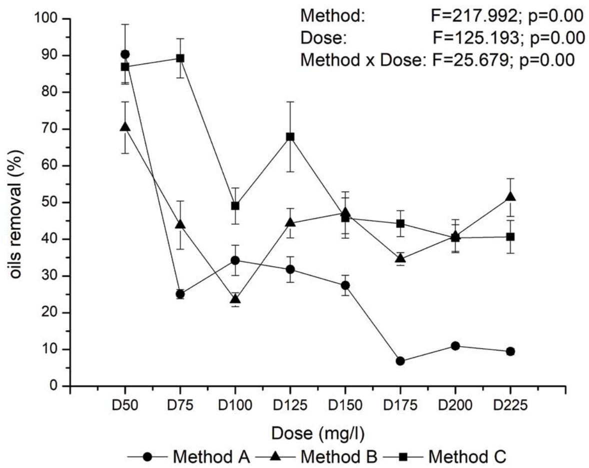

Fig. 4. Oil (C12–C35) removal percentage efficiency using the coagulation; A – aluminum sulfate(VI), B – iron(III) chloride, C – ultrasounds, and iron(III) chloride.

achieve the best environmental effect. While in the research of Abbas et al [14], TPH removal efficiency of *Escherichia* sp. strain UIWRF0110 was 90%, for *Chryseobacterium* sp. strain AJ0 with 84%. Steliga et al [21] during biological treatment achieved decreases in TPHs content in oily wastewater of 91% for the consortium.

3.2. Treatment using coagulation and oxidation

The chromatographic analyzes of the content of petrol (C6–C12) and oil (C12–C35) by FID chromatography indicated high content of TPHs (C 6–12 1558.77 mg/L and C 12–35 7426.61 mg/L). By analyzing the content of petrol and oil in the tested material, the TPHs removal percentage efficiency was calculated using the oxidation and coagulation methods (Figs. 3–5).

The highest petrol removal (90%) (Fig. 3) using coagulation treatment was obtained for the lowest coagulant dose treatment, regardless of the treatment method used (at D50 no significant difference observed). The lowest ratio for petrol removal was obtained for aluminum sulfate coagulation (10%–35%) regardless of the dosage with the exception of D50- the lowest dosage of coagulant. In the research of Bruno et al. [22] the investigated batch tests also confirmed that aluminum sulfate ($Al_2(SO4)_3 18H_2O$) was the most effective coagulant, even more, if combined with the polyelectrolyte A57. Moreover, the highest removal ratio was obtained for C method treatment- ultrasounds and iron(III) chloride. Puszkarewicz et al. [4] also conducted coagulation studies on oil removal from wastewater. The initial oil concentration in the emulsion was 360 mg/L. The lowest oil concentration for $FeCl_3 * 6H_2O$ was observed at the dose of 150 mg/L, and this coagulant proved to be more effective than aluminum sulfate. For this coagulant ($Al_2 (SO_4)_3\ 18H_2O$) the dose of 180 mg/L turned out to be the most optimal dose.

The highest oil removal (90%) (Fig. 4) using coagulation treatment was obtained for the lowest coagulant dose (D50) for A treatment and D50 and D75 for C method treatment. While increasing the coagulant dose the oil removal was decreasing (A) up to 10% of removal or was constant regardless of the treatment (B, C – 40% removal). It has also been found in studies carried out by Piekutin et al. [8] where the higher dose of the coagulant used, the higher the concentration of TPHs and the lower the ratio of TPHs removal.

In the conducted study the effect of contact time was not investigated, since the results are already reported and indicated that increasing the treatment time does not improve the removal and degradation of TPHs present in the oily wastewater and sludge [23]. To compare a similar content of TPHs (1,500–1,800 mg/L) was removed in wastewater samples achieving 100% removal when combined flocculation, coagulation, and deflector was used [22].

When Fenton's reaction was applied the removal efficiency was very high (over 99%), regardless of the treatment applied (iron to hydrogen peroxide ratio) (Fig. 5). This

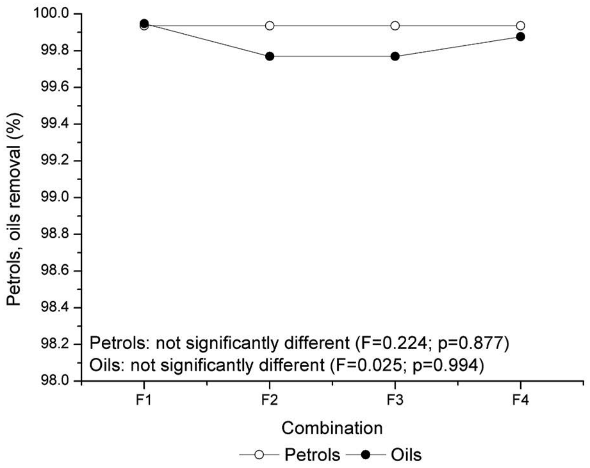

Fig. 5. Petrol (C6–C12) and oil (C12–C35) removal percentage efficiency using the Fenton's method; ratio of Fe^{2+}: H_2O_2; F1-1:6, F2-1:10, F3-1:3, F4-1:5.

phenomenon was observed both for petrol and oil removal. Fenton's reaction applied for petroleum-derived compounds resulted in the highest TPHs removal among all treatments. This is probably due to very high oxidizing potential. Moreover, in the tests carried out by Piekutin et al. [8] on six different concentrations of petroleum compounds, an aeration process was additionally used to increase the TPHs and improve the overall process efficiency.

Sivagami et al. [9] found the combined both ultrasound and Fenton's treatment as a promising technology for the removal of recalcitrant organic pollutants from spill sludge. The sono-Fenton was also used in the degradation of PAHs in textile dyeing sludge, as well as degradation of naphthalene in soil or oxidation of 4-chlorophenol [9]. The Ultrasonication process induces micromixing and microstreaming mechanisms, making the sludge particles disrupted. This could enhance the interaction between the OH radicals and contaminant particles which results in the enhanced use of Fenton's reagents in the oxidation [24]. Sivagami et al. [9] achieved less removal efficiency up to 85%, but the treated material was petroleum oil spill sludge. The efficiency of Fenton's treatment of petroleum contaminated wastewater in comparison to oily sludge is higher due to better interaction of hydroxyl radicals with TPHs. The results of the investigated study confirm that Fenton's reaction treatment is very effective for petroleum contaminated wastewater, even regardless of the applied Fe^{2+}:H_2O_2 ratios, while for petroleum contaminated sludge, as confirmed by Sivagami et al. [9] the combined sono-Fenton is required. Kozak and Włodarczyk-Makuła also applied the modified Fenton process in the degradation of low molecular weight PAHs [25]. In the research of Sun et al. [26], when only ozonation was applied the non-selective oxidation towards all petroleum hydrocarbons in microbubble ozonation system was noted, and the reduction of petrol in oil fraction was found to be in the range of 70%–80% within 2 h, while the initial concentration of TPHs was 8,000 mg/kg of sludge. Direct ozonation using a microbubble system is quite effective compared to Fenton's method since the generation of secondary wastes is limited, but this process requires more sophisticated devices and additional energy consumption.

3.3. Results of statistical analysis

In the case of methods A, B, and C, the two-way analysis of variance revealed the effect of method and dose of coagulants and the interaction of both two parameters on the concentration of oil and petrol removal degree. As shown in Figs. 3–5, *F*-values indicated that the interaction of the mentioned variables was less significant than a method and salt dose individually. For the biological treatment methods (Fig. 2), the treatment conditions did not have a statistically significant effect on the removal of TPH compounds. However, it should be noted that type of microbial had significantly impact on the concentration of petrol (F = 9.763; p = 0.005), while the molar ratio in Fenton's process affected concentration (removal) of oil (F = 64.964; p = 0.00).

4. Conclusions

In a conducted study the biological, chemical, and physical treatment of TPHs contaminated wastewater and sewage sludge was tested. It was found that the highest TPHs removal efficiency (99%) of both petrol and oil in wastewater was achieved when the Fenton's reaction was applied. As an innovation aspect, this procedure can, therefore, be an effective tool in removing TPHs from sludge and wastewater from petroleum and oil separators, especially as pre-treatment methods. The experimental results also confirmed that the degradation of TPHs fractions in oily wastewater was significantly improved when using the combined methods. Fenton's reaction applied to petroleum-contaminated wastewater seems to be the fastest method of TPHs removal in comparison to standard coagulation or biological method. Therefore, in the aspect of time requirement of contaminants removal and the possibility of ex-situ process the application of a chemical-physical treatment is more favorable than biological treatment since the effect of hydrocarbons plays an inhibitory role in microorganisms growth. The novelty of this work is based on the possible application of the described method as a simple pretreatment of wastewater in petroleum separators in order to increase the emptying time periods of the device. More research is now required to adopt the process conditions to lab-scale oil separator operation.

Acknowledgment

This work was supported by an internal research grant BS/PB 401/304/11 and BS/PB 400/301/20 of Czestochowa University of Technology.

References

[1] M. Włodarczyk-Makuła, Threat of pollution of the aquatic environment with petroleum compounds, LAB Laboratories, Apparatus Res., 21 (2016) 12–16 (in Polish).
[2] H.I. Abdel-Shafy, M.S. Mansour, A review on polycyclic aromatic hydrocarbons: source, environmental impact, effect

on human health, and remediation Egypt, J. Petrol., 25 (2016) 107–123.
[3] P.M. White, W.D. Kirkpatrick, D. Wolf, G.J. Thoma, Phytoremediation of Crude Oil Contaminated Soil, International Petroleum Environmental Conference, Fayetteville, 2001.
[4] A. Puszkarewicz, J. Kaleta, D. Papciak, The use of activated carbons for the treatment of oily aqueous solutions, Eng. Environ. Prot., 12 (2009) 153–161 (in Polish).
[5] I.C. Ossai, A. Ahmed, A. Hassan, F.S. Hamid, Remediation of soil and water contaminated with petroleum hydrocarbon: a review, Environ. Technol. Innovation, 17 (2020) 100526.
[6] H. Kim, S. Park, Y. Choi, S. Lee, J. Choi, Fouling due to $CaSO_4$ scale formation in forward osmosis (FO), reverse osmosis (RO), and pressure-assisted forward osmosis (PAFO), Desal. Water Treat., 104 (2018) 45–50.
[7] W. Ouyang, T. Chen, Y. Shi, L. Tong, Y. Chen, W. Wang, J. Yang, J. Xue, Physico-chemical processes, Water Environ. Res., 91 (2019) 1350–1377.
[8] J. Piekutin, The use of coagulation and reverse osmosis for petroleum hydrocarbons removal from water, Desal. Water Treat., 128 (2018) 437–441.
[9] K. Sivagami, D. Anand, G. Divyapriya, Treatment of petroleum oil spill sludge using the combined ultrasound and Fenton oxidation process, Ultrason. Sonochem., 51 (2019) 340–349.
[10] A. Rosinska, L. Dąbrowska, Selection of coagulants for the removal of chosen PAH from drinking water, Water, 10 (2018) 886.
[11] A. Grobelak, P. Kokot, D. Hutchison, A. Grosser, M. Kacprzak, Plant growth-promoting rhizobacteria as an alternative to mineral fertilizers in assisted bioremediation-sustainable land and waste management, J. Environ. Manage., 227 (2018) 1–9.
[12] P. Sarkar, A. Roy, S. Pal, B. Mohapatra, S.K. Kazy, M.K. Maiti, P. Sar, Enrichment and characterization of hydrocarbon-degrading bacteria from petroleum refinery waste as potent bioaugmentation agent for in-situ bioremediation, Bioresour. Technol., 242 (2017) 15–27.
[13] O.O. Alegbeleye, B.O. Opeolu, V.A. Jackson, Polycyclic aromatic hydrocarbons: a critical review of environmental occurrence and bioremediation, Environ. Manage., 60 (2017) 758–783.
[14] S.Z. Abbas, T.C. Whui, K. Hossain, A. Ahmad, M. Raftullah, Isolation and characterization of oil-degrading bacteria from marine sediment environment, Desal. Water Treat., 136 (2018) 282–289.
[15] S. Dealtry, A.M. Ghizelini, L. Mendonça-Hagler, R.M. Chaloub, F. Reinert, T.M.P. Campos, N.C.M. Gomes, K. Smalla, Petroleum contamination and bioaugmentation in bacterial rhizosphere communities from *Avicennia schaueriana*, Braz. J. Microbiol., 49 (2018) 757–769.
[16] S.J. Varjani, V.N. Upasani, A new look on factor affecting microbial degradation of petroleum hydrocarbon pollutants, Int. Biodeterior. Biodegrad., 120 (2017) 71–83.
[17] A. Grobelak, K. Czerwińska, A. Murtaś, General Considerations on Sludge Disposal, Industrial and Municipal Sludge, In: Industrial and Municipal Sludge, Butterworth-Heinemann, 2019, pp. 135–153.
[18] A. Grosser, E. Neczaj, M. Madela, P. Celary, Ultrasound-assisted treatment of landfill leachate in a sequencing batch reactor, Water, 11 (2019) 516.
[19] P. Zacharyasz, J. Siepak, J. Rosada, Petroleum-contaminated soil and water analysis and biodegradation, Pol. J. Environ. Stud., 21 (2012) 1467–1480.
[20] N. Dombrowski, J.A. Donaho, T. Gutierrez, K.W. Seitz, A.P. Teske, B.J. Baker, Reconstructing metabolic pathways of hydrocarbon-degrading bacteria from the deepwater horizon oil spill, Nat. Microbiol., 1 (2016) 16057.
[21] T. Steliga, P. Jakubowicz, P. Kapusta, Changes in toxicity during treatment of wastewater from oil plant contaminated with petroleum hydrocarbons, J. Chem. Technol. Biotechnol., 90 (2015) 1408–1418.
[22] P. Bruno, R. Campo, M.G. Giustra, M. De Marchis, G. Di Bella, Bench scale continuous coagulation-flocculation of saline industrial wastewater contaminated by hydrocarbons, J. Water Process Eng., 34 (2020) 101156.
[23] P.D.A. Mello, F.A. Duarte, M.A. Nunes, M.S. Alencar, E.M. Moreira, M. Korn, V.L. Dressle, E.M. Flores, Ultrasound-assisted oxidative process for sulfur removal from petroleum product feedstock, Ultrason. Sonochem., 16 (2009) 732–736.
[24] S. Chakma, V.S. Moholkar, Physical mechanism of sono-Fenton process, AIChE J., 59 (2013) 4303–4313.
[25] J. Kozak, M. Wlodarczyk-Makula, Degradation of low molecular weight PAHs in the modified Fenton process, Annu. Set Environ. Prot., 20 (2018) 1418–1429.
[26] Z. Sun, F. Xia, Z. Lou, X. Chen, N. Zhu, H. Yuan, Y. Shen, Innovative process for total petroleum hydrocarbons reduction on oil refinery sludge through microbubble ozonation, J. Cleaner Prod., 256 (2020) 120337.