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Application of the Hybrid Chemical-Biocatalytic Approach for Conversion of Nitrocellulose-Containing Sewage Sludge

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Abstract: Waste containing explosive chemicals are hazardous to the environment. We suggested and implemented a hybrid approach for the destruction of nitrocellulose-containing sewage sludge (NCS) from a real chemical industrial complex. Combining chemical alkaline hydrolysis and mesophilic anaerobic digestion in a up-flow anaerobic sludge blanket (UASB) reactor allowed us to successfully achieve the balance between the environmental safety and economic efficiency of the stages of the treatment. After the alkaline treatment of waste at 50 °C with 1.5 M KOH, the solid residue contained mostly just sand and no nitrocellulose (NC). The liquid phase accumulated 2869 ± 24 mg N-NO_2^-/L and 1698 ± 51 mg N-NO_3^-/L. Bioconversion of the liquid phase neutralized with acetic acid and diluted with water by a factor of 50 in a 1 L UASB reactor ensured 99% efficiency of extracting $N_{(NO_2^- + NO_3^-)}$ and chemical oxygen demand (COD). Further, biogas with high methane content (>70%) was obtained. The establishment of the operational regime in the UASB reactor was achieved in two stages. The suggested hybrid approach to denitrification and methanogenesis is aimed at implementing the sustainable development concept in industrial chemical cycles. The results of this study are significant for researchers and technologists interested in developing hybrid processes for waste treatment that involve chemical catalysis as the first stage.

Keywords: nitrocellulose; waste; anaerobic processes; hybrid catalysis; denitrification; biogas

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1. Introduction

NC is widely used in industry and medicine, and its production rate is steadily growing [1]. Wastewater from the industrial production of NC contains its residues [2]. The long-established process for the treatment of such industrial waste much used in practice includes the stage of accumulation of such waste in technical settling pools. Nitrocellulose tends to gradually accumulate in the sediment in such pools [3]. Electrocoagulation, flotation, and electrochemical methods are among the more modern approaches to removing NC from wastewater [2]. Note that waste or sediment from the settling pools with high content of NC (with a nitrogen content of more than 12%) are highly flammable and explosive [1]. Environmental pollution with explosive chemicals is a grave problem. The eco-efficient treatment of NC-containing sludge from the sediment of technical settling pools, implementation of a safety management system, and government supervision can help to avoid mistakes within the chemical industry which can lead to a massive explosion of hazardous waste. Until recently, the main approach to the disposal of NC in waste was incineration. Nowadays, all industrial technologies are being steadily transformed towards achieving the goals of sustainable development, energy efficiency, and environmental safety [4]. The final aim of waste treatment is achieving complete mineralization of the pollutants and transformation of the waste into commercial products [5]. The introduction of biocatalytic stages into the technological protocols for waste treatment is one of the

perspective approaches for achieving these goals [6]. The use of biocatalysts in waste treatment processes facilitates achieving several aims formulated in the sustained development concept: 6 (Ensure availability and sustainable management of water and sanitation for all) and 12 (Ensure sustainable consumption and production patterns). The advantages of biocatalytic stages with anaerobic sludge in waste treatment protocols are their ability to biotransform a wide range of chemical components into commercial biogas with low energy consumption. The liquids produced at the output of biocatalytic stages usually have low toxicity and require minimal additional treatment before they can be released into the environment [4,6]. Multiple examples show that the most efficient treatment of waste is possible by combining the physical, chemical, and biological approaches [5,6]. Thus, looking for the most efficient and safe way of treating nitrocellulose-containing waste become very topical recently [3].

Combining physicochemical and biological approaches to waste treatment can be either sequential or simultaneous so that, in the latter case, both processes are going on in parallel in the same reactor [7,8]. Waste treatment in a single reactor involving different techniques can reduce the overall treatment time by obviating the necessity of transition from one stage to another. However, such processes are difficult to implement since chemical agents can be toxic to the biocatalysts. The known successful examples of realizing such processes are mostly connected with combining biocatalysts with nanoparticles and nanomaterials [8–10]. Introducing Cu@Fe_3O_4 or TiO_2@Ag nanoparticles into a reactor containing anaerobic sludge ensured a decrease in hydrogen sulfide content in the produced biogas and an increase in methane production efficiency [9,10]. Combining polyvinylpyrrolidone-coated magnetite nanoparticles and oil-degrading bacteria ensured 100% degradation of petroleum within 48 h or less. Application of bacteria alone could provide the degradation degree of 80–90% after 24–48 h. The observed effect was due to the sorption of petroleum on the nanoparticles, which increased the bioavailability of this substrate [11]. In the case of NC-containing waste, the sequential treatment process involving chemical hydrolysis as the first stage can be more efficient and easy to realize.

Alkaline hydrolysis is one of the perspective approaches to treating nitrocellulose waste [12–14]. The action of alkali can ensure the decomposition of nitrocellulose within a relatively short time and at relatively low temperatures (below 60 °C), forming nitrite ions, nitrate ions, and biologically degradable components [13]. The mechanisms of the chemical processes involved in the alkaline hydrolysis of NC are well studied with various modern techniques, including those of computer simulation [14–17]. KOH and NaOH can provide the best results in terms of hydrolytic activity towards NC among the available agents (such as KOH, NaOH, $Ca(OH)_2$, and ammonia solution) [1]. However, the known studies in this field do not pay enough attention to the possibilities of large-scale implementation of environment-efficient processes for treating NC-containing waste emanating from real industrial installations.

Anaerobic biocatalytic transformation of media produced via the alkaline chemical treatment of "problematic" nitrogen-containing organic waste is a perspective approach both in terms of environmental safety and energy efficiency. In contrast to the aerobic biocatalysts, the anaerobic biocatalytic consortium can achieve biotransformation of nitrate and nitrite ions into environmentally neutral molecular nitrogen, whereas the residues of the organic substrates can be converted into biogas, which is a valuable commercial product. Additional biocatalysts and electron donors can also be introduced into the reaction medium in order to enhance the efficiency of biocatalytic transformation [18].

A new hybrid chemical-biocatalytic approach for the destruction of nitrocellulose-containing sewage sludge (NCS) from a real chemical industrial complex has been proposed and approbated in the present study for the first time. The hybrid approach of NCS conversion was realized by combining the following sequential stages: alkaline treatment of NCS with the accumulation of nitrite and nitrate ions; sedimentation and separation of the obtained reaction mass into the liquid and the solid phase via natural settling and

decantation; neutralizing the liquid phase to pH of 7.5 with iced acetic acid and subsequent biocatalytic transformation of thus obtained liquid under anaerobic conditions (Figure 1).

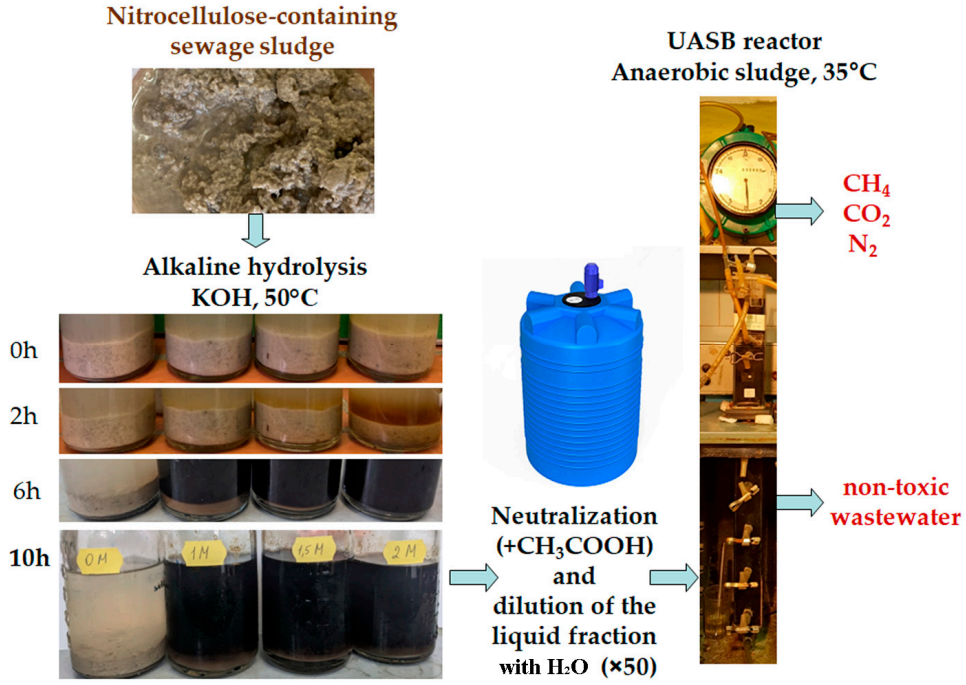

Figure 1. Schema of the hybrid chemical-biocatalytic approach for the treatment of NCS from a real chemical industrial complex.

A mesophilic anaerobic sludge was successfully applied as a biocatalyst engaging the components of the diluted liquid fraction in the denitrification and methanogenesis processes at 35 °C during the gradual introduction of this liquid into a UASB reactor.

2. Materials and Methods

2.1. Materials and Biocatalyst

NCS with characteristics shown in Table 1 was obtained from a sludge collector of the Aleksin Chemical Industrial Complex (Tula, Russia) and was used as test material.

Table 1. Initial characteristics of nitrocellulose-containing sewage sludge.

Parameter	Value	Parameter	Value
pH	6.5 ± 0.05	C (mg/kg on a dry matter basis)	722 ± 17
Moisture content (%)	86 ± 0.2	N-NH_4 (mg/kg on a dry matter basis)	69 ± 1
NC (g/kg on a dry matter basis)	617 ± 9	C:N ratio	25:1
OM (g/kg on a dry matter basis)	82 ± 10	MM (g/kg on a dry matter basis)	301 ± 19

NC, OM, and MM refer to nitrocellulose, organic matter, and mineral matter, respectively.

Mesophilic anaerobic sludge was taken from the Frito Lay plant (Kashira, Moscow, Russia); its characteristics were described previously [19]. The chemicals used in this study were purchased from Sigma (St. Louis, MO, USA).

2.2. Alkaline Hydrolysis of NCS

Alkaline hydrolysis of NCS was performed at 35 °C, 50 °C, or 65 °C for 10 h in 120 mL glass flasks. A flask was loaded consecutively with 10 g of the initial NCS and 70 mL of 1 M, 1.5 M, or 2 M KOH aqueous solution. A flask with 10 g NCS and 70 mL of distilled water was used as a control (Figure 1). Samples of the liquid phase were taken after 10 h, and the concentration of nitrates, nitrites, and COD was measured therein. Then, the liquid

phase was separated via decanting, and the residue was tested for the presence of NC, OM, and MM.

2.3. Anaerobic Fermentation in UASB Reactor

The initial inoculum concentration of mesophilic anaerobic sludge in 1 L UASB reactor was 30% (*v*/*v*). The description of the UASB reactor was given in previous work [20]. The stage of adapting the active sludge to the presence of nitrate and nitrite ions took 18 days (while the hydraulic retention time (HRT) was 3 days) in a mineral medium with 0.4 g/L of glucose, 20 mg/L of KNO_3, 25 mg/L of KNO_2. Then, the liquid fraction produced after the alkaline hydrolysis of NCS was introduced into the reactor. The process of bioconversion of the liquid fraction produced after completing the alkaline hydrolysis of NCS and diluting the resulting liquid by a factor of 50 was performed via the gradual introduction of this liquid into the bioreactor at 35 °C in two stages with different volumes of the HRT: (I) adaptation period (HRT was 2 days) and (II) operational regime (HRT was 1 day). Reactor parameters and also Influent and Effluent parameters are given in Table 2. Samples for determining the analytic parameters of the medium were taken every second day during all stages.

Table 2. Parameters of bioconversion in the UASB reactor of media obtained after alkaline hydrolysis of NCS, neutralization with acetic acid, and dilution of the resulting solution with water by a factor of 50 *.

Operation Mode	I	II
Duration (day)	20	22
Reactor parameters		
HRT (day)	2	1
NLR (mg $N_{(NO_2^- + NO_3^-)}$/L/day)	45.7	91.4
OLR (mg COD/L/day)	334	668
Influent parameters		
pH	7.5	7.5
$N_{(NO_2^- + NO_3^-)}$ (mg/L)	91.3	91.3
COD (mg/L)	668	668
Effluent parameters **		
pH	7.8	7.8
$N_{(NO_2^- + NO_3^-)}$ (mg/L)	1.7	1.2
COD (mg/L)	13.4	13.4
Biogas (mL/L)	360	360
CH_4 in biogas (%)	72	74
N_2 in biogas (%)	10.0	10.0
Calculated parameters **		
$N_{(NO_2^- + NO_3^-)removal}$ (%)	98	99
$COD_{removal}$ (%)	98	99

* The standard deviation (±SD) of data from three independent experiments were less than 5%. ** The data are given for the final measurement in the Operation mode. HRT—the hydraulic retention time; NLR—the nitrogen loading rate; OLR—the COD loading rate.

2.4. Analytical Methods

The humidity of NCS was determined via the standard gravimetrical technique [21]. The content of NC in the samples was evaluated based on the difference in the mass of the dry aliquot of the sample before and after annealing NC. The content of the organic matter (OM) in the samples was determined by keeping the dry aliquot in a muffle oven PM-4 (PlavkaPro, Moscow, Russia) at 600 °C to constant weight. In order to evaluate the content of MM, the mass of NC and OM was subtracted from the aliquot mass.

The content of carbon in the samples was determined via the chemical oxygen demand (COD) measured in a water extract after keeping it for one hour according to the known technique [19,22]. In order to prepare the water extract, a precisely measured aliquot was mixed with 10 mL of double distilled water. The quantitative content of carbon was

calculated via the previously described technique [22]. The techniques for determining the pH, and quantity of the mobile forms of nitrogen (via the Nessler method) were described in detail previously [21,23].

2.5. Accumulation of Biogas and Determination of Its Content

The total pressure and biogas concentration in the gas phase were measured. The content of nitrogen, methane, and carbon dioxide in the gas phase was measured with an LKhM 8 MD chromatograph (Zarya, Dzerzhinsk, Russia) Model 3 with a katharometer (the carrier gas was argon with 20 mL/min flow rate). 2 m long columns were filled with Q porapak (Sigma-Aldrich, St. Louis, MO, USA). The oven temperature was maintained at 50 °C, and the retention times of nitrogen, methane, and carbon dioxide were 61, 67, and 82 s, respectively.

The data were shown as means of at least three independent experiments ± standard deviation (±SD). Statistical analysis was realized using SigmaPlot 12.5 (ver. 12.5, Systat Software Inc., San Jose, CA, USA). The significant ($p \leq 0.05$) differences between obtained results were estimated by one-way analysis of variance (ANOVA).

2.6. Characterisation

The scanning electron microscope (SEM) Hitachi TM-3030 (Hitachi Ltd., Tokyo, Japan) with energy dispersive X-ray spectroscopy (EDS) system Quantax 70 (Bruker Nano GmbH, Berlin, Germany) was used to characterize the surface morphology of the NCS samples. The samples were placed on watch glasses and dried in a laboratory oven (SNOL 20/300, AB UMEGA GROUP, Utena, Lithuania) for two hours.

3. Results

3.1. Optimizing the Conditions for Performing Alkaline Hydrolysis of NCS

The alkaline hydrolysis of NCS from a chemical industrial complex involved a rather fast dissolution of the sludge (Figure 1). Higher alkaline concentrations and higher temperatures caused an increase in the reaction rate. An almost complete dissolution of the solid fraction was observed within 10 h in the temperature range of 50–65 °C for all the alkaline concentrations used in the experiments (Figure 1). The insoluble substance was left at the bottom of the flask and consisted mostly of sand (OM—1.2 ± 0.1% (*w*/*w*); MM—98.8 ± 0.1% (*w*/*w*), NC—not detected). The liquid fraction separated via decantation from all the samples was found to contain nitrite and nitrate ions (2580–2985 mg $N\text{-}NO_2^-$/L, 1246–1702 mg $N\text{-}NO_3^-$/L).

The analysis of the results obtained within the multi-factor experiment (Figure 2) allowed us to determine the conditions optimal for alkaline hydrolysis in terms of the rate and efficiency of transforming the nitrogen present in NCS into a soluble form. These are 1.5 M KOH, 50 °C. Though the alkaline hydrolysis of NCS from a chemical industrial complex was performed for the first time in this study, the rate of operational temperatures and alkaline concentration were chosen based on the previous results obtained for alkaline treatment of nitrocellulose and NC-containing waste [12,14,17].

Alkaline hydrolysis of NCS under optimal conditions was successfully scaled up by a factor of 10 (after mixing 100 g NCS with 700 mL 1.5 M KOH, complete decomposition of NC was achieved within 10 h at 50 °C). The amount of soluble nitrogen compounds in the medium was 2869 ± 24 mg $N\text{-}NO_2^-$/L and 1698 ± 51 mg $N\text{-}NO_3^-$/L, and the pH of the solution was 13.5. In order to reduce the total nitrogen content in the resulting solution to below the environmentally acceptable level for industrial wastewater (<10 mg/L [24]), an additional purification stage should be added to the denitrification process.

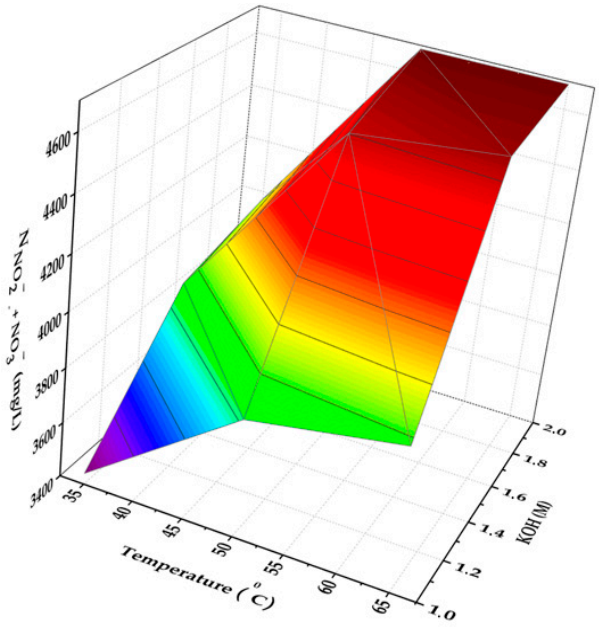

Figure 2. Results of accumulation of nitrite and nitrate ions in the liquid fraction under various conditions of NCS alkaline hydrolysis.

Alkaline treatment under optimal conditions allows for achieving complete decomposition of the NC fibers (Figure 3) contained in the explosive NCS from a real chemical industrial complex within a relatively short time (10 h).

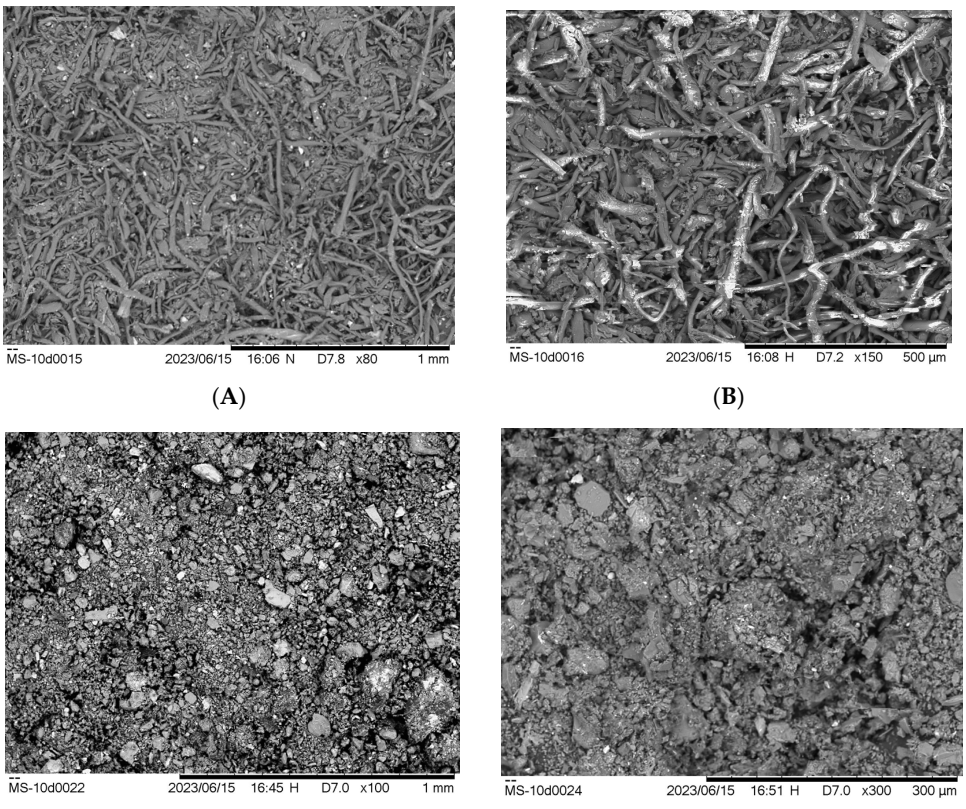

Figure 3. SEM images of the initial sample of NCS (**A**,**B**) and the insoluble substance after alkaline hydrolysis of NCS with 1.5 M KOH (**C**,**D**).

3.2. Biocatalytic Conversion of the Liquid Fraction Produced via the Alkaline Treatment of NCS

Additional purification following the alkaline treatment of the liquid fraction was performed in a UASB under anaerobic conditions using mesophilic anaerobic sludge. The operational range of the medium's pH was 7.0–8.5 in order to achieve the maximum target activity of the biocatalyst. The total concentration of the oxidized forms of nitrogen in the medium $N_{(NO_2^- + NO_3^-)}$ < 100 mg/L was also an important factor. Therefore, the pH of the liquid medium was reduced to 7.5 by adding iced acetic acid prior to introducing this liquid into the bioreactor. The COD of the resulting solution was 33.4 g/L. In order to reduce the nitrogen content to within the optimal operation range, the liquid fraction was diluted with water by a factor of 50 before putting it into the bioreactor (Figures 1 and 4, Table 2).

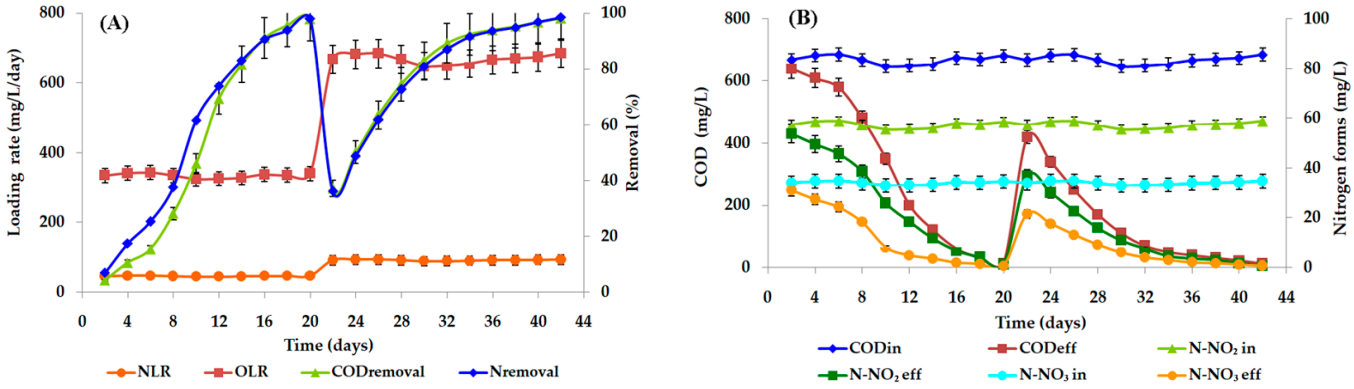

Figure 4. The experimental data and calculated parameters of bioconversion in the UASB reactor of media obtained after alkaline hydrolysis of NCS: Reactor and Calculated parameters (**A**); Influent and Effluent parameters (**B**).

Achieving the operational regime was performed in two stages, with a gradual increase in the nitrogen load of the reactor by reducing the hydraulic retention time.

At the beginning of the operational mode I (within the first 5 days), the $N\text{-}NO_2^-{}_{removal}$ factor did not exceed 40%, which indicates an adaptation period of the biocatalyst. After 20 days, the biocatalyst has almost completely adapted to the components of the medium in terms of engaging them in the biocatalytic conversion processes producing biogas and molecular nitrogen. This allowed reducing the nitrite and nitrate-ion load of the reactor by a factor of 2 during the following conversion stage (Figure 4). The liquid fraction obtained via alkaline hydrolysis was successfully purified within 22 days under the conditions of phase II. COD and the concentration of the nitrogen compounds were reduced to within the regulation levels for industrial wastewater (Table 2). The UASB reactor that has achieved the operational regime can be further used for additional treatment of wastewater in the flow-through regime. This technique was proven to be efficient for treating the wastewater produced via alkaline hydrolysis of NCS and containing nitrite and nitrate ions, whereas the NCS itself was taken from a real chemical industrial complex.

4. Discussion

While the tendency persists towards transforming the industrial chemical processes to achieve the ultimate goal of sustainable development, companies are encouraged to include environmental management into their daily management approaches and also to reduce the output of pollutants and prevent their discharge into the environment [25]. Recycling the previously accumulated waste, which was earlier just stored in technical storage facilities, is a topical task. NCS from a real chemical industrial complex, which is the subject of the present study, is one of such waste types which can be recycled using novel approaches. Following the modern trend of the circular economy while developing processes for waste treatment, the chemicals contained in the pollutants can be considered

as a potential raw material supply. On the other hand, tapping into this resource should in itself minimize the harmful impact on the environment [26].

All the above-discussed considerations were taken into account while developing the suggested setup for a hybrid process for NCS treatment (Figure 1). On the one hand, the process setup is sufficiently simple in terms of the technologies involved and the viability of their practical realization. On the other hand, it allows to most profitably combine the maximum environmental friendliness and economic efficiency. The combination of the chemical and biological stages within the hybrid process is the key to achieving both the environmental and economic benefits of NCS treatment. The introduction of biocatalysts into the process provided minimal environmental impact while simultaneously producing biogas with high methane content (>70%), which is a commercial commodity. Thus implementation of this process yields both a commercial product and non-toxic waste complying with the strictest standards in terms of the content of carbon and nitrogen compounds (Table 2), whereas the solid residue contains almost exclusively the sand from the bottom sediment of the settling pool which initially contained NC (Figure 3). Introducing the chemical pre-treatment of NCS as the initial stage and the consequent use of a flow-through UASB reactor allowed reducing the overall duration of the process and provided the conditions for the most efficient functioning of the anaerobic sludge in terms of implementing denitrification and methanogenesis processes. Note also that the resulting biogas can be separated into valuable components (such as CH_4 and N_2) for the implementation of C-1 green chemistry processes or those involving the production of nitrogen-containing organic and inorganic compounds [4]. Several efficient approaches are known to separate nitrogen and methane. These include the use of organometallic frameworks [27,28], zeolites, porous carbons, and porous organic frameworks [29].

While developing the proposed hybrid process, essential attention has been paid to finding the optimum conditions ensuring the best combination of the sequential stages of the chemical treatment and biological catalysis. The components of the medium produced via chemical catalysis and other preparatory manipulations should have maximum compatibility with the anaerobic sludge [4,18]. Therefore, KOH was chosen as the alkaline agent and acetic acid as the neutralizing one. Compared with the other candidates for the role of the alkaline agent, the application of KOH ensured both the most favorable conditions for NC decomposition [1] and the functioning of the sodium–potassium pump within the live cells of the anaerobic sludge [30]. Compared with other candidates for the role of neutralizing agent, acetic acid is one of the most available and environmentally friendly agents, which can moreover be produced from renewable raw materials and even waste substances [31]. On the other hand, acetate is a donor of electrons as well as a substrate for performing the target catalytic reactions by the anaerobic sludge cells, which ensure denitrification and methanogenesis [32]. Acetic acid is currently actively used for developing a wide range of novel processes [33,34]. Acetate is generally considered the next-generation platform substrate in future industrial biotechnology [35].

Note also that the concentration and the temperature regime of the alkaline treatment of the NC-containing waste play a key role in terms of the accumulation of certain target products in the reaction medium. Depending on the conditions of the experiment, in addition to the accumulation of soluble forms of nitrogen-containing ions in the medium, decomposition of the cellulose itself can be observed [36]. Therefore, while optimizing the conditions for the implementation of the chemical stage of the suggested hybrid process, the temperature regime and alkaline concentration were chosen based on the known published data [13,14,17,36] with a focus on achieving the complete destruction of NC and accumulation of the components most suitable for the subsequent biotransformation. Compared to the known processes involved in the studies of alkaline hydrolysis of NC within the timeframe of 10–1200 min [13,14,17,36], the duration of this chemical stage in the present study was relatively high at 600 min. This is due to using NCS from a real chemical industrial complex rather than pure NC in this research. The completion of the alkaline treatment coincided with the termination of the process of NCS dissolving in the alkaline

solution. Therefore, the concentration of nitrite ions in the resulting solution was higher than that of the nitrate ions (Figure 2), which fits the published data [13,17].

Reducing the inhibiting influence of the resulting medium's components (such as nitrite ions) which are potentially toxic for the live components of the medium, was ensured by diluting the solution before its introduction into the UASB reactor (Figure 1). The advantages of the chosen bioreactor type include the possibility of using it in a flow-through continuous mode. These high-rate systems, able to perform anaerobic reactions at reduced hydraulic retention time, have an obvious advantage compared to traditional digesters [37]. On the other hand, we can note increased water consumption as one of the drawbacks of the suggested hybrid process. Further optimization of the process can involve replacing water with solutions based on wastewater or pre-treated waste with low nitrogen content, which are perspectives for biogas production [38]. However, this possibility is the subject of a separate study.

The total duration of the hybrid process of treating 100 g of NCS under the above-described experimental conditions using a 1 L UASB reactor was 42 days, while 99% efficiency of removing $N_{(NO_2^- + NO_3^-)}$ and COD was provided. A proportional increase in the process rate can be achieved by increasing the reactor volume while preserving the reactor parameters of phase II. The obtained results are obviously superior to those known for degrading a similar NCS under anaerobic conditions. The maximum NC removal efficiency in the previous studies was 55.1% after 31 days, and no commercially valuable product was obtained then [3].

While developing new and optimizing the known hybrid processes involving activated sludge, all the possible inhibiting factors that can influence (directly or indirectly) the target biochemical reactions should be taken into account. The key factors for the biocatalyst activity of the sludge are the availability of the substrate and the ratio of COD to the target ion concentration or that of the total N, P, S. In the case of biocatalytic treatment of alkaline hydrolysates of NCS, nitrates and nitrites were the target ions. Acetic acid was used as the source of COD and substrate in order to balance the COD/Ntot. This acid also played the role of a neutralizing agent. Only ratios exceeding 6/1 are allowed to suppress the inhibition of the target biocatalytic reactions of methanogenesis and denitrification. When the ratio of COD to target ion or total N, P, and S concentrations are unbalanced, the activity of the biocatalyst in the bioreactor can be essentially inhibited. Thus while removing sodium glutamate from wastewater at a low ratio of COD/sulfates, the accumulation of sulfide and the competition for the substrate between the sulfate-reducing bacteria and the methane-producing archaea have led to an essential inhibiting inside the anaerobic reactor [39]. Simultaneous fermentation of several wastes of different origins can be a perspective way to increase treatment efficiency [4,18,40,41]. This approach is capable of finely controlling and finding the optimal ratio of COD to target ion or total N, P, S and will probably be used in the future for further optimization of the NCS treatment process suggested in this study. The efficiency of the treatment of complex waste can also be increased via digestate recirculation [40]. In addition to methane, anaerobic conversion of waste can also produce such a valuable commercial product as hythane (a mix of 10–30% v/v of H_2 and 70–90% v/v of CH_4) [41]. Thus anaerobic degradation of waste is a perspective process that has a high potential for optimization and combination with other processes.

The suggested hybrid approach with alkaline hydrolysis as the first stage is a perspective for treating poultry [6] and other agricultural waste, which can contain such dangerous micropollutants as mycotoxins. In addition to the degradation of the components of such waste into bioaccessible compounds, alkaline hydrolysis can ensure the destruction of a wide range of mycotoxins [6].

The results obtained in the present study are of interest to researchers and engineers engaged in studying processes of treating nitrocellulose-containing waste. Further, the approaches and the results of this study are significant for researchers and technologists interested in developing hybrid processes for waste treatment that involve chemical catalysis as the first stage.

5. Conclusions

Combining chemical alkaline hydrolysis and anaerobic biocatalytic treatment in a UASB reactor provides a perspective approach to the treatment of nitrocellulose-containing waste. The treatment process is balanced in terms of environmental safety and economic efficiency. The conversion of nitrocellulose-containing sewage sludge from a real chemical industrial complex results in obtaining a commercial product (biogas with high methane content), non-toxic wastewater, and solid residue containing mostly sand and no NC. The resulting biogas, if necessary, can be separated into valuable components (such as CH_4 or N_2) for implementing C-1 green chemistry processes or those producing nitrogen-containing compounds. The development of hybrid processes involving the initial chemical stage should include the optimization of the conditions ensuring the best possible combination of the subsequent stages of chemical and biological catalysis. The chemicals used during the chemical catalysis should provide the maximum efficiency of the reaction. The components of the medium obtained after the chemical catalysis and other preliminary manipulations should ensure high biocompatibility with live cells and, when possible, should be available for biotransformation into environmentally friendly compounds.

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