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Physical and Chemical Features of The Thermolysis of Wastewater Sludge

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Abstract

The global concern regarding the disposal of municipal wastewater sludge is pressing. Contaminated water influxes into wastewater treatment channels, causing a surge in sludge volume and requiring additional processing. Pyrolysis of domestic wastewater sludge emerges as a promising solution, transforming waste sludge into reusable secondary raw materials. Our study employs a uniquely designed batch reactor system to uncover outcomes from laboratory-based thermal processing of domestic wastewater sludge. Within the reactor, the feedstock undergoes a series of processes, including dehydration, depolymerization, partial decomposition, and the removal of water. Additionally, decarboxylation occurs, leading to the formation of pyrolysis resins, achieved by combining dehydration and decarbonylation processes. This comprehensive process yields solid, liquid, and gaseous carbonaceous hydrocarbon residues. The chemical composition, structure, and properties of these pyrolysis products are thoroughly examined through analytical characterization techniques. Our findings reveal that sludge pyrolysis accomplishes thermal sterilization, resulting in valuable carbonaceous residue with potential applications as fuel or raw materials for petrochemical synthesis. Moreover, during pyrolysis, heavy metals such as cadmium and mercury can be extracted from the carbonaceous residue. Importantly, this process generates additional energy, and operating below 500 °C prevents dioxin contamination in the environment.

Keywords: Sludge; Wastewater; Processing; Utilization; Pyrolysis; Batch reactor; Composition; Hydrocarbon composition; Material balance.
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1. Introduction

The growth of industrial activity inevitably leads to an increase in the volume of wastewater used in the process of washing the extracted material and in the accumulation of sludge deposits.[1] According to the USEPA, any biosolids byproduct generated from the wastewater treatment plant either due to urbanisation, growth in population, comsumption changes and increased industrialisation is referred to as sewage sludge.[2] Sewage sludge is a valuable organic matter that can be useful in the production of fertlizer enhancing soil fertility and plant growth but if imporoperly managed could cause health and other environmental problems.[2] Therefore, finding effective ways to utilize them is one of the most important tasks in any industrial sector. Sewage sludge, the inevitable by-product of municipal wastewater treatment plant operation, is a key issue in many countries due to its increasing volume and the impacts associated with its disposal.[3,4] Thermochemical processing offers a new way of managing sewage sludge, not only by providing effective volume reduction, but also enabling transformation of carbon-rich organic fraction into valuable energy and fuel.[4] Owing to some unique properties, sewage sludge differs from other solid fuels such as lignocellulosic biomass and coal, making its thermochemical conversion application somewhat complicated and challenging.[5] There are three main ways of utilizing sludge deposits in the world practice, depending on the final residue: Processing in agriculture and urban landscaping sectors as fertilizer, by thermal decomposition processes (incineration, pyrolysis, *etc.*) and through landfill deposition.[6]

The first method of utilizing sludge deposits by processing is the most relevant, but it can only be achieved after minimizing the negative impact on human health and the

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environment, by reducing the concentration of toxic compounds and completely eliminating pathogenic microorganisms.[7]

From the literature data, it is known that the pyrolysis process is very relevant since the products of sludge processing can be used as secondary raw materials.

The aforementioned requirements can be fully met through the pyrolysis processing of sludge, which provides useful products from the processing. During pyrolysis, thermal sterilization occurs, and derivative products are formed (gas, liquid, solid carbon residue), which can be used as fuel or as raw materials for petrochemical production.[8] Additionally, heavy metals (such as mercury and cadmium) can be separated along with the carbon residue during pyrolysis.[9]

There are two main types of reactions that occur during the pyrolysis of sludge under normal conditions:

1) thermal decomposition of the initial substance and further breakdown of the resulting intermediate compounds

2) condensation and polymerization of molecules formed during the primary degradation reactions of the raw material.

The product exiting the pyrolysis apparatus is a complex mixture of gaseous, liquid, and solid substances, the composition of which depends on the chemical nature of the raw material and the physical parameters of heating.[10]

In this research project, the analysis of sludge sediment samples obtained from different locations within the oil and gas field of the West Kazakhstan region was investigated for the physicochemical properties before and after pyrolysis. The results obtained clearly revealed the carbonaceous hydrocarbon composition in the sludge after pyrolysis, which makes it a viable platform for fuel and raw materials production in the petrochemical industry.

2. Materials and Methods

2.1 Sewage sludge sampling

The specific location where the sludge sediment sampling was conducted is shown in Fig. 1. The sludge sediments were found to be situated in a pit at different locations within the west Kazakhstan region and were distinguished from one another based on their stage of natural dehydration over various years. Point A was used for the collection of sediment from 2015-2016, point B for sediment from 2017-2018, and point C for sediment from 2019. The sludge samples were collected within the summer season of the year and pyrolyzed at specific temperature and the physicochemical properties were analyzed after.

2.2 Process parameters

In the studied research, the efficacy of pyrolysis, one of the chemical methods for treating the sludge produced during the wastewater treatment process was analyzed. The choice of pyrolysis method, such as thermal decomposition of waste and converting it into useful products, is our main goal, which solves the problem of valorization of industrial waste. Our study was conducted under laboratory conditions using a batch reactor system.[11,12] While maintaining the rules for conducting research and processing the material, laboratory studies were carried out with the aim of creating industrial installations for sludge processing. The experimental setup for pyrolysis is depicted in Fig. 2. Thermal processing was performed on a metallic reactor with a gas outlet at the top for gaseous products and a liquid outlet at the bottom, which was equipped with a cooler.

In the reactor, the process of dehydration of the feedstock is carried out, accompanied by its depolymerization and partial decomposition and accompanied by the removal of water, decarboxylation with the formation of pyrolysis resins by combining the processes of dehydration and decarbonylation. The batch reactor system labeled as reactor #2 in Fig. 2, was used to carry out the pyrolysis process on a prepared 100-gram sample. Before starting the process, the setup was checked for airtightness and purged with an inert gas (helium) for 30 minutes to remove air from the system. The process was conducted at atmospheric pressure. The heating of the reactor and sample was achieved using a temperature-controlled furnace #4 in the temperature range of 20-21 °C to 700-800 °C until the formation of reaction products ceased. The temperature in the reaction zone was monitored by sensor #22. Liquid products were condensed in a cooled receiver labeled as receiver #7, while uncondensed gases were collected in gasometer #20 after passing through trap #10 and manometer #11.

Table 3 provides the parameters and mode of the pyrolysis process, as well as the quantities and conditions of intensive gas evolution. The carbonaceous product was extracted from the container (after cooling) and weighed with an accuracy of 0.01 g. The mass of supernatant (pyrogenic) water and resin was determined.

Fig. 1 The sludge sediments were found in a pit located within the West Kazakhstan region. Sampling sites for silt sediment at various stages of natural dehydration in different years: Sediment from 2015-2016 was collected at point A; Sediment from 2017-2018 was collected at point B; Sediment from 2019 was collected at point C.

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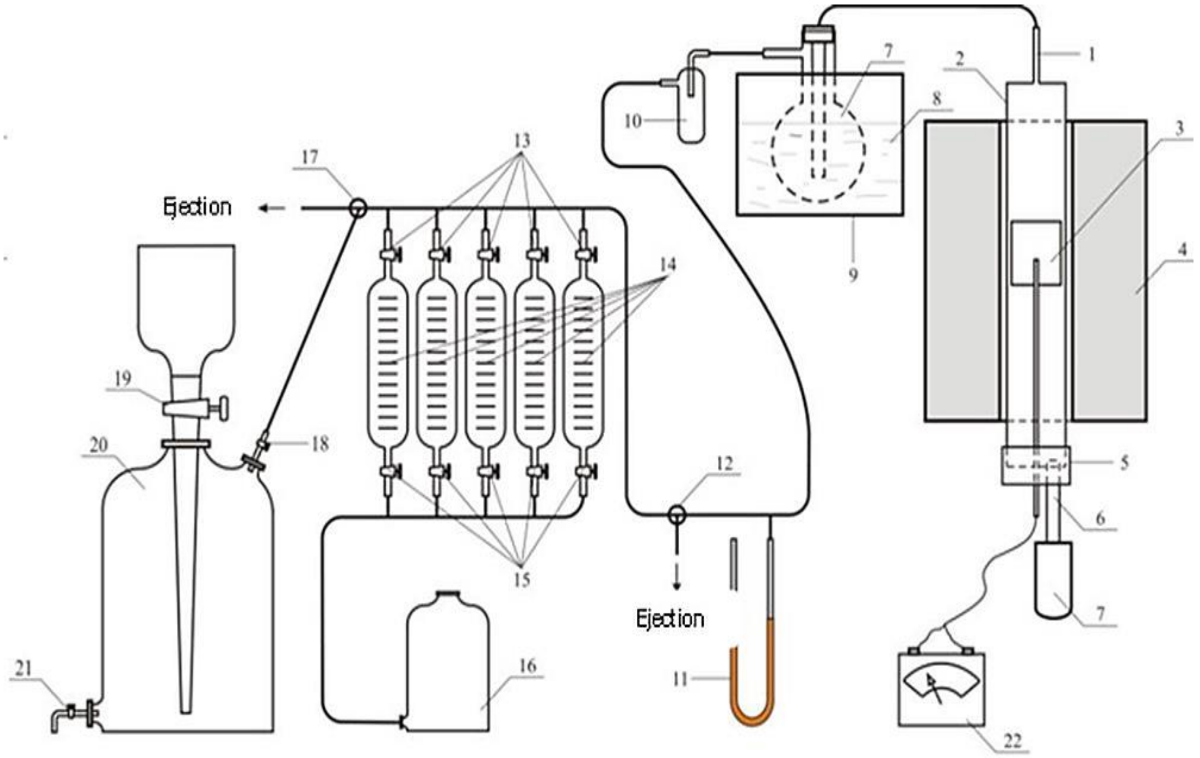

Fig. 2 Schematic diagram of the pyrolysis unit: 1 - gas supply tube; 2 - reactor; 3 - raw material container; 4 - thermostatic furnace; 5 - screw cover; 6 - discharge tube; 7 - receiver; 8 - cooling mixture; 9 - water bath; 10 - trap; 11 - pressure gauge; 12, 13, 15, 17, 18, 19, 21 – valves; 14, 20 – gas meters; 16 – feed tank; 22 – temperature sensor.

2.3 Characterization techniques

Various physicochemical methods were employed to investigate the obtained pyrolysis products. The surface area of the solid residue of pyrolyzed sludge sediment was determined using the BET method. The BET method was used to directly measure the adsorption capacity and pore size of powdered samples under high vacuum conditions. A sample of the investigated substance was degassed under a vacuum at a temperature of 200 °C for two hours. Then the adsorption isotherm was taken on a high-speed Quantachrome NOVA gas sorption analyzer, combined with special software. Nitrogen was used as the absorbate. All calculations were carried out on a personal computer connected to the Quantachrome NOVA analyzer.

The surface area of solid materials was measured using the Brunauer-Emmett-Teller (BET) method. The BET method is used to measure the volume of a monolayer on the surface of the adsorbent, and the number of molecules in the monolayer. By determining the area occupied by one molecule, the total surface area of the adsorbent, regardless of its shape and porosity, can be determined. The BET method is typically accurate within a range of 5-10% over the relative pressure (P/P_0) range of 0.05-0.35.

To determine the pore size distribution, the Barrett-Joyner-Halenda (BJH) method was used. The model is based on the assumption of cylindrical pores and that the pore radius is equal to the sum of the Kelvin radius and the thickness of the adsorbed film on the pore wall. The BJH method uses the desorption or adsorption branch of the isotherm in the pressure range of 0.967 - 0.4 P/P_o as the input data for calculations.

X-ray phase analysis was carried out using a DRON-8T multifunctional X-ray diffractometer (JSC Burevestnik Research Center, St. Petersburg, Russia). In order to study the composition and distribution of alloying elements in multiphase alloys. The samples were ground in an agate mortar, and the powders were placed in a cuvette 2 mm deep. The diffraction patterns were recorded using CuKα radiation, a Goebel parabolic mirror, and a Mythen 2R1D position-sensitive detector with a resolution of 0.0144°. Registration was carried out by points with a step of 0.2°, exposure time at a point was 4 s. The diffraction patterns were processed using the programs of the Burevestnik Research Center, and qualitative analysis was carried out using the PDF-2 database version 2.2102 (2021).

Pyrolysis gas analysis was carried out using a Crystal-2000 chromatograph with two isotherms (80-110 ^{o}C) and two 2-meter-long columns filled with Porapac Q and zeolite 5A sorbents, respectively. A chromatograph was used to study qualitative and quantitative characteristics. The Porapac Q column separated hydrocarbon components $(C_1 - C_6)$ in the gas, while the zeolite 5A column separated methane and hydrogen. The detector temperature was set at 140 ^{o}C, and the carrier gas flow rate was 50 mL/min. The analysis time was 20 minutes. Liquid product analysis was performed using a Crystal-5000

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chromatograph with a linear temperature program from 35 °C to 250 °C. The composition analysis was carried out using a flame ionization detector (FID), and the components were identified by logarithmic retention indices. The concentrations of components, average molecular weights, relative densities, saturated vapor pressures, octane numbers, and boiling temperatures were calculated using the Chromatek Analyst program, specifically developed for detailed hydrocarbon analysis.

3. Results and discussion

Based on experiments obtained in laboratory conditions, it was revealed that sludge is a complex multi-component system. Despite the presence of pathogenic bacteria in the composition of sewage sludge, changes in the diversity of such microbial communities depend on the duration of natural drying. During this process, under the influence of unfavorable environmental factors such as temperature fluctuations and UV radiation, a microbial structure close to permissible with a predominance of representatives of natural microflora is formed.[13–15]

Table 1 presents the results of the chemical analysis of sludge samples taken from several points in the sludge site located within the Western Kazakhstan region.

As can be seen from the table, the pH values fluctuated between 6.95-7.41, indicating a neutral environment. Carbonate ions were absent in the sludge samples. Organic matter in the samples from different points demonstrated uniform values ranging from 2.36% to 2.52%, which was not characteristic of other detected ions such as calcium, magnesium, potassium, chlorides, and bicarbonates. The concentration of chloride ions exceeded the permissible limit. Presumably, chlorine solutions were used for the disinfection and treatment of household wastewater before sludge formation. The sample from the fourth point showed high concentrations of anions and cations in all indicators. This is because the sludge sample was stored for the shortest duration. The results of laboratory research on the organic substances in the investigated samples of sludge are presented in Table 2. X-ray diffraction, thermogravimetric, and infrared spectroscopic analyses have shown that 25-30% by mass of the organic component included synthetic surfactants, ethers, extractable components (fats, oils, *etc*.), petroleum products (light and medium fractions of tarry substances), and nitrogen-, oxygen-, and phosphorus-containing organic compounds.

The comprehensive thermographic analysis of wastewater sludge demonstrated its thermal stability in the temperature range of 105 to 180 °C, after which the process of thermo-oxidative degradation of the organic components began. It should be emphasized that in addressing the issue of sludge disposal, especially for large treatment plants, the following requirements should be considered:

- All sludge must be fully utilized, regardless of the presence of harmful substances;
- The method of disposal should not pose a threat to the environment, including human health;
- The resulting products should be useful for utilization;
- The economics of the chosen method of disposal should be profitable.

The formation of these pyrolysis products was observed in a wide temperature range and the yield of products depends on the heating rate of the raw material, as can be seen in Tables 3 and 4. From Table 3, the influence of time duration, temperature, and volume plays a major role in the amount of gases released. The optimal conditions were obtained in the range 30-60 minutes, 220-490 oC, and 6000-10500 mL shows an abundant gas release meanwhile other process parameters gave no results as expected.

The ratio of the obtained products mainly depends on the temperature of the process, as well as on the content of organic substances in the original product and its moisture content, as can be seen from the diagram in Fig. 3. The results obtained from experimental analysis of wastewater sludge studied the heating rate at 10, 20 and 30 deg/min for solid residue, liquid and gaseous fractions.

Table 1. Results of chemical analysis of sludge sediment.

Sampling area	pH of water extract	Cation-anion composition. mg per 100 g of soil					Organic matter, %
		Ca^{2+}	Mg^{2+}	K^+	HCO^{3-}	Cl^-	
1	7.07	585.2	84	8.132	23.18	103.87	2.36
2	7.37	135.2	30	16.4	29.28	45.44	2.4
3	7.41	145.2	21.12	3.393	38.43	54.24	2.36
4	7.34	940	-	56.16	167.75	542.39	2.44
5	7.23	655.2	30	3.081	47.58	67.71	2.52
6	6.95	715.2	54	8.522	32.33	117.69	2.4
7	7.14	660	45.12	29.445	51.85	126.56	2.36
8	7.11	480	36	22.425	29.28	99.61	2.36
Threshold limit value	6.5-8.5	Not standardized	Not standardized	Not standardized	<100	<35	2.1-4.0%

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Table 2. Organic components of sludge from industrial and municipal wastewater.

№	Name of the substance	Quantity, mg/kg
1	Synthetic surfactants (surfactants)	1850–1900
2	Ester-extractable compounds (fats, oils, *etc.*)	140-180
3	Petroleum products	4,20-7,88
4	Phenols	No
5	Formaldehyde	Not detected

Table 3. Process parameters for monitoring the release of gases during pyrolysis.

Duration of	Process parameters and notes		
experiment, min	t, °C	V (gas), ml	Results
0	80	0	-
15	140	2000	-
30	220	6000	abundant gas release
45	380	8500	abundant gas release
60	490	10500	abundant gas release
75	590	11700	-

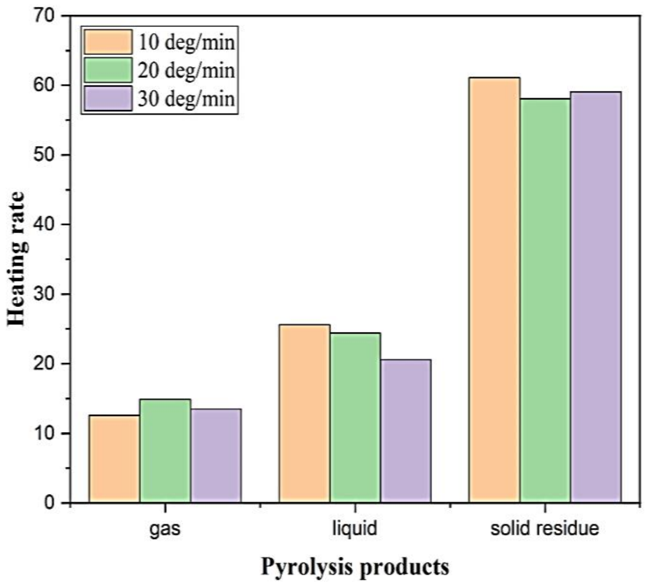

Fig. 3 The ratio of the products obtained by the aggregate state.

In the context of the pyrolytic conversion process, the solid residue, known as technical carbon, has garnered significant attention as reported by researchers[16,17]

To gain preliminary insights into the structural and particle characteristics of the materials under investigation, this study conducted an electron microscopic analysis of sludge sediments before and after the pyrolysis process.

The imaging was carried out using a Hitachi S-4800 scanning electron microscope, and the resulting images are presented in Fig. 4 SEM study of wastewater sludge before and after pyrolysis showed a change in the morphology, becoming more irregular, porous, loose, and rough. The observed modifications were most likely caused by pyrolysis's heat deterioration, physical disintegration, and chemical changes.

The porous and rough structure may boost the adsorption capacity, leading to better wastewater treatment and possibly resource recovery. However, difficulties with handling and processing could occur. To fully comprehend the effects of these morphological alterations, additional studies should quantify changes in porosity and chemical composition.

To verify these properties, the sludge sediment underwent pyrolysis and was subsequently evaluated as a sorbent. To assess the potential applications of the resulting solid residue, essential characteristics such as density and specific surface area were investigated using laser diffraction and low-temperature nitrogen adsorption.[18,19]

The BET method was employed to determine the adsorption-desorption properties of nitrogen on the surface of the pyrolysis residue under laboratory conditions at 800 ºC. The specific surface area of the solid residue was found to be 154 m^2/g, indicating its potential use as a sorbent, while the total pore volume was determined to be 0.042 cm^3/g. Based on the obtained results of the solid residue adsorption properties studies, it was found that the creation of a sorbent based on solid residues after pyrolysis of the sludge from domestic wastewater is a promising method for industrial applications. In order to identify the crystalline phases, X-ray diffraction phase analysis of the objects was carried out. Diffraction patterns of sewage sludge before and after pyrolysis are shown in Fig. 5. The diffraction pattern of the original sludge from sewage treatment indicates the presence of replicas corresponding to the following compounds: SiO_2 - 63%, $H(AlSi_2)O_6$ - 2%, $CH_8N_4O_3S$ - 12%.

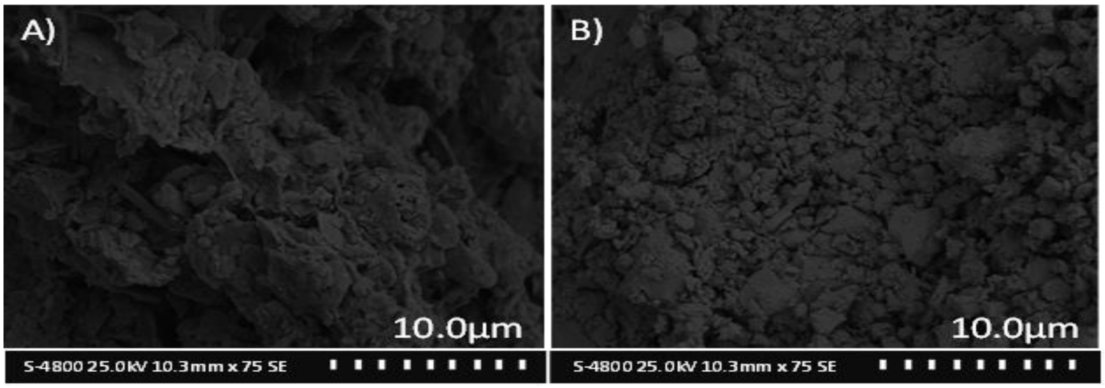

Fig. 4 Sludge sediment of wastewater: (A) before the pyrolysis process, (B) after the pyrolysis process.

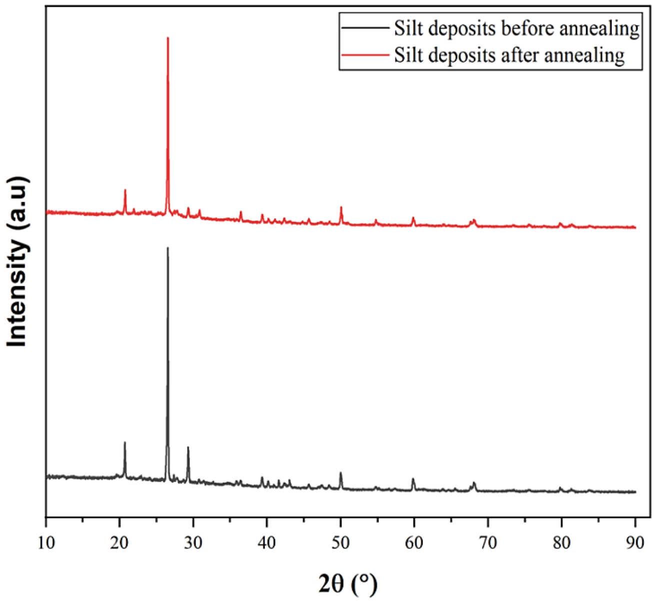

Fig. 5 Comparison of diffraction patterns of silt deposits before and after annealing.

The diffraction pattern of the silt deposit after annealing indicates the presence of signals from the following compounds: SiO_2 - 71%, Na-Al-Si-O - 9%, $H(AlSi_2)O_6$ - 9%, FeS - 7%. As a result of annealing of the sludge sample, the formation of an iron sulfide phase occurs, which indicates the presence of various organic and inorganic sulfur compounds in the original sludge.

A study of the gas component after pyrolysis on a chromatograph was carried out with the separation of components on I_2/charcoal and Porapak columns. The obtained chromatograms allowed for the calculation of the mass of the collected pyrolysis gas. Chromatographic analysis revealed that changes in heating rate affect both the qualitative and quantitative composition of the gas, as shown in Table 4. The diverse composition of the produced gas, high concentration of light hydrocarbons, and the presence of hydrogen highlight its potential for use as a feedstock for organic synthesis and as a valuable source of liquid hydrocarbon fuel components.

The gas was found to contain hydrogen, carbon monoxide, and C_1-C_5 hydrocarbons, which contributed to its high calorific value. This calorific value was determined to be sufficient for maintaining high temperatures within the pyrolysis furnace and supporting the process in any mode. The combustible gas generated during pyrolysis was found to contain approximately 70 wt.% of combustible components and had a calorific value of up to 4000 kJ/m^3. The combustible gas served a dual purpose as a fuel source for the pyrolysis reactor and as a coolant for the feedstock dryer, as demonstrated in prior research.[3,20]

The liquid product of pyrolysis was subjected to fractionation using atmospheric distillation in order to determine the composition and quantity of each fraction. During the distillation process, a single fraction was obtained in the temperature range of 75-100 °C. However, any further attempts to increase the temperature resulted in the formation of a heavy residue that foamed and prevented the distillation of higher-boiling fractions.

Table 4. The composition of the gas produced during the pyrolysis of sludge residue.

Compound	Composition of pyrolysis gas, %		
	10 °C/min	20 °C/min	30 °C/min
H_2	31.9	2.1	12.2
air	4.7	0.6	4.5
CO	14.3	1.9	13.4
CO_2	32.3	39.8	37.1
CH_4	10.3	50.7	30.3
C_3H_6	3.5	3.2	1.6
C_3H_8	0.2	0.5	0.1
C_4H_8-1	-	-	0.7
n-C_4H_{10}	1.2	0.7	-
i-C_4H_{10}	0.9	0.2	0.1
C_4H_8-2	0.2	0.1	-
n- C_5H_{12}	0.2	-	-
i- C_5H_{12}	0.1	-	-
C_5H_{10}	0.1	0.2	-
$C_5H_{10\text{-}1}$	0.1		-
Total	100	100	100

The liquid product obtained after settling was observed to stratify into two layers. The upper layer, characterized by a yellow oily appearance, exhibited an unpleasant odor. On the other hand, the bottom layer, which appeared as a yellowish mobile liquid, possessed a very strong and unpleasant odor. During the settling process, the accumulation of gas above the liquid was also observed. It is speculated that the accumulation of gas above the liquid might have contributed to the observed pungent odor, and the wet indicator paper test revealed a pH value of 11-12 upon contact with the liquid.

The residue remaining after distillation was found to be a black, highly viscous substance at room temperature. Although it is combustible, incomplete combustion occurs, releasing soot which may be attributed to the presence of high-carbon condensed systems in the residue.

To further investigate the composition of the liquid product, chromatographic analysis was performed using a "Crystal-5000" chromatograph. The results of the analysis for the upper layer of the liquid are presented in Table 5.

The process of slow pyrolysis generates liquid products that contain a wide range of valuable compounds. Fractional distillation of these liquids can yield diverse products, including paraffins, arenes, asphaltenes, carboxylic acids, phenols, and organic bases, which have widespread applications in industries such as fuel and chemical synthesis. The graph displayed in Fig. 6 shows that the liquid product obtained by pyrolysis of the sludge is enriched in isoparaffinic

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Table 5. Light fraction of liquid product of sludge pyrolysis obtained from the chromatographic analysis, wt%.

Group	Paraffins	Isoparaffins	Aromatics	Naphthenes	Olefins	Oxygenates	Total
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.1	0.0	0.1
5	0.0	0.0	0.0	0.0	0.0	0.2	0.2
6	0.0	0.1	0.5	0.0	0.3	0.0	0.9
7	0.5	0.1	11.0	0.0	1.2	0.0	12.8
8	1.8	1.5	5.4	3.4	0.6	0.0	12.7
9	0.3	11.4	1.4	2.0	1.1	0.0	16.3
10	0.1	6.4	1.2	1.5	0.3	0.0	9.4
11	0.0	4.4	4.1	0.2	0.0	0.0	8.8
12	0.0	0.1	2.8	0.0	0.0	0.0	2.9
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.6	0.0	0.0	0.0	0.0	0.0	0.6
Total	3.4	24.0	26.3	7.1	3.6	0.2	64.6

Table 6. The main components of the liquid product of sludge pyrolysis.

No	Retention time, minutes	Component	Weight, %	Volume. %	Mole, %
1	26.938	3,4-dimethylhexane	1.129	1.271	1.423
2	33.225	2,4-dimethylhexane	1.470	1.610	1.739
3	36.698	Toluene	10.963	9.952	14.775
4	43.725	3-ethylmethylcyclopentane	2.486	2.551	2.751
5	46.155	n-octane	1.821	2.041	1.980
6	47.703	2,3,5-trimethylhexane	5.202	5.310	5.164
7	57.889	Ethylbenzene	3.059	2.777	3.578
8	60.378	2,3-dimethylheptane	4.276	4.383	4.236
9	64.893	3-ethylheptane	3.809	4.127	3.688
10	65.944	o-xylene	3.752	3.567	3.050
11	68.666	naphthenes C_{7-9}	4.059	4.377	3.930
12	71.029	i-butylcyclopentane	5.771	5.795	5.726
13	81.974	2,3-dimethyloctane	4.214	4.295	4.060
14	85.460	1,2,4-trimethylbenzene	4.188	4.068	3.974
15	86.993	naphthenes C_{10-13}	2.710	2.882	2.365
16	97.353	naphthenes C_{11-17}	3.245	3.451	2.578
17	98.512	1,2-dimethyl. 3-ethylbenzene	2.154	2.037	1.767
18	106.951	arenes C_{11-18}	1.778	1.572	1.510
19	107.919	arenes C_{12-15}	1.239	1.095	0.948

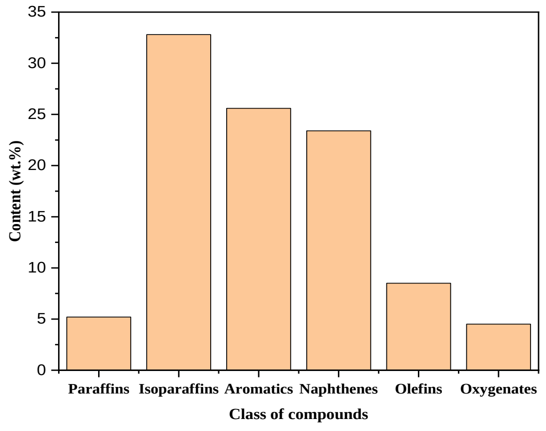

Fig. 6 Group composition of the liquid product of sludge pyrolysis.

(32.8%), aromatic (25.6%), naphthenic (23.4%), while there are also small amounts of olefinic hydrocarbons (8.5%), paraffin (5.2 wt.%), and oxygenates (4.5 wt.%).

The conducted chromatographic analysis made it possible to detail the hydrocarbon composition of the light fraction of the liquid product (Table 6).

Fractionation of the liquid showed that the octane number of the low-boiling fraction (up to 100 °C) is 76.8 points according to the motor method, 93.3 points according to the research method, with details of the contribution to the octane number of compounds of different classes.

In overall, the research method showed a higher result for the class of compounds obtained as compared with the motor method. Isoparaffins are most abundant hydrocarbons released while oxygenates are nearly zero for both methods. Based on

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the data obtained, it can be concluded that the liquid obtained during the pyrolysis of the sludge can be considered as a fuel.

4. Conclusion

In summary, the pyrolysis of sludge obtained from the wastewater treatment process has been shown to yield various carbonaceous products, including gases, liquids, and solids, as determined through the employed characterization methods. The quantity of these products significantly depends on the heating rate of the raw material.

The sludge residue emerges as an economically viable and environmentally sound sorbent for oil and its byproducts, with the spent sorbent finding potential use as a filler in asphalt-bitumen mixtures. The gas generated during pyrolysis possesses a chemical composition and calorific value suitable for processing in a gas fractionation plant, yielding liquefied gas that can serve as fuel or a heating source for pyrolysis furnaces. Additionally, the liquid product, a complex mixture of hydrocarbons, can be utilized as a mixed fuel containing a light fraction with a high-octane number.

In essence, these findings underscore the promise and safety of sludge pyrolysis as a solution to environmental challenges. This research contributes to the advancement of green chemistry and technology, specifically in the development of effective, low-toxic materials with a wide range of applications. It also aids in improving the environmental conditions in the region, promoting the rational economic use of natural resources, and fostering the growth of a "green economy." By reducing harmful emissions, recycling waste, and fostering environmentally friendly industries, this approach enhances the investment attractiveness of both the industry and the region. Furthermore, it addresses waste disposal issues by producing export-oriented commercial products and mitigating environmental pollution, ultimately reducing the adverse impact on the environment.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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