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The characteristics changes and efficient cleaning mechanisms of sludge hydrothermal carbonization and tempering under different hydrothermal reaction conditions

Xiaohang Ma[1]*, Yepu Li[1], Zonghua Wang[1], Yingxiang Xia[2], Jun Zhang[1], Chao Huang[2], Xiaoran Liu[1], Yanting Zheng[1]

[1] *School of Water Resources and Environment Engineering, Nanyang Normal University, Nanyang, China.*
[2] *Nanyang Zhonghui Sludge Treatment and Resource Utilization Co., Ltd. Nanyang, China.*

***Corresponding author:** 20132071@nynu.edu.cn

Original Research

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Abstract:

In response to the problems of high energy consumption, high maintenance costs, and significant environmental impact in traditional sludge treatment schemes, strict control of conditions is required. This study investigates the effect of different raw materials, water temperatures, additives, and physicochemical pretreatments on the hydrothermal carbonization and tempering of sludge through hydrothermal reactions. The experimental results indicate that the calorific value of the hydrothermal carbon after ultrasonic pretreatment shows an overall decreasing trend with the increase of ultrasonic energy density. Its maximum value is 6.61 MJ/kg, and the corresponding sound energy density is 0.6 W/ml. In addition, the calorific value of the hydrothermal carbon after pre-treatment with the agent shows a wave like downward trend as the initial liquid hydrogen ion concentration index of the sludge increases. When the hydrogen ion concentration index reaches 7, its hydrothermal carbon calorific value is the smallest, which is 6.31 MJ/kg. But its calorific value is also 3.3% higher than that of untreated hydrothermal carbon. The study reveals the effective cleaning mechanism of sludge under different reaction conditions, and provides scientific basis and technical support for the field of sludge treatment.

Keywords: Hydrothermal reaction; Carbonization quenching and tempering; Sludge; Physical and chemical pretreatment; Cleaning mechanism

1. Introduction

Sludge is an organic waste generated during urban sewage treatment, and its treatment and disposal have always been an important issue in the field of environmental protection [1]. Hydrothermal carbonization, as an effective sludge treatment technology, achieves the resource utilization of sludge by converting it into hydrothermal carbon under high temperature and pressure conditions. However, there are still some issues with the hydrothermal carbon produced during the hydrothermal carbonization process, such as the emission of volatile organic compounds and the presence of heavy metals [2, 3]. To improve the quality of hydrothermal carbon and reduce its potential impact on the environment, researchers have begun to explore the characteristic changes of sludge hydrothermal carbonization and conditioning under different hydrothermal reaction conditions. Then they delved into its efficient cleaning mechanism. Traditional sludge treatment methods such as landfill and composting have problems such as high energy consumption, high maintenance costs, and being greatly affected by environmental factors. Therefore, it is necessary to seek more efficient and clean sludge treatment solutions. Hydrothermal carbonization technology is a new type of sludge treatment method.

Table 1. Materials and reagents required for the experiment.

Reagent	Specifications	Manufacturer	Quantity
Baking soda	AR	Komio Chemical Reagents Co., Ltd	500g
Ethanol	30.0%	-	1L
Concentrated sulfuric acid	95%	Shanghai Aladdin Technology Co., Ltd	500mL
Nitric acid	ACS,70%	Shanghai Aladdin Technology Co., Ltd	2L
Heavy metal standard solution	National Material Metrological Standards	-	100mL

It can convert sludge into carbon rich solid products under certain temperature and pressure conditions, while achieving reduction and resource utilization.
Huang et al. investigated the nitrogen conversion of sewage sludge by adjusting temperature and adding Ca/Na acetate to investigate its effect on nitrogen conversion during hydrothermal carbonization process. The results show that an increase in temperature caused more nitrogen to shift towards water and oil products, while the addition of acetate promoted nitrogen hydrolysis [4]. Researchers such as Ipiales et al have proposed a method that combines hydrothermal carbonization and anaerobic digestion to address the issue of wet biomass waste treatment. The results show that this strategy can effectively reduce organic load, produce methane rich biogas, and contribute to energy recovery [5]. Almahbashi et al. proposed a method of using sewage sludge as raw material to produce activated carbon in response to the increasing volume of sewage sludge. They optimized the preparation conditions through Box Behnken design using response surface methodology, exploring the effects of chemical activation ratio, contact time, and activation temperature on the surface area of activated carbon. The results show that the optimized activated carbon has a higher surface area [6]. This study conducted hydrothermal reactions through pretreatment, hydrothermal reaction, solid carbon treatment, gas product treatment, liquid product treatment, and product utilization to regulate the hydrothermal carbonization of sludge. Then it investigated the effects of different raw materials, water temperatures, additives, and physicochemical pretreatments on the hydrothermal carbonization of cement. It is expected that this study will provide important reference for the development of efficient and clean hydrothermal carbonization and tempering technology. This can contribute to solving the problem of sludge treatment in urban sewage treatment plants.

2. Experimental equipment

The experiment involved many common chemical reagents, including baking soda, alcohol, concentrated sulfuric acid, nitric acid, etc. The specifications and manufacturer information of these reagents are shown in Table 1 Baking soda is used as a regulator or catalyst in this experiment. Ethanol is used as a solvent or reactant. In the process of hydrothermal carbonization, it may help increase the solubility of organic matter in sludge and promote the progress of the reaction. Concentrated sulfuric acid is used as an acid catalyst here to regulate the acidity and alkalinity of the system [7, 8]. It can catalyze some chemical changes in hydrothermal reactions and also help regulate pH values, further affecting the carbonization process of sludge and the solubility of heavy metals. Nitric acid is used in the digestion process of sludge to help convert heavy metals in the sludge into soluble forms for subsequent analysis and measurement. Heavy metal standard solutions are used for quantitative and calibration of heavy metal elements in experiments [9, 10]. By comparing the heavy metal content of experimental samples and standard solutions, the migration, transformation, and fixation patterns of heavy metals during hydrothermal carbonization can be studied. This is of great significance for evaluating the effectiveness and environmental risks of hydrothermal carbonization treatment. The instruments used in the experiment are shown in Table 2. Electric constant temperature blast drying oven (DHG-970A), which can be used for drying sludge samples after hydrothermal carbonization. By controlling temperature and humidity, sludge samples under different drying conditions can be obtained. Box type resistance furnace (SX-4-10), which can be used to provide a high-temperature environment and simulate hydrothermal reaction processes under different temperature conditions. By adjusting the temperature of the resistance furnace, the effects of temperature on the physicochemical properties, heavy metal fixation, and pollutant emissions of sludge during hydrothermal carbonization process can be studied [11, 12]. Graphite heating plate (DB-1EFS) provides a uniform heating environment to maintain temperature uniformity and stability during hydrothermal reactions. Electronic scales can be used to accurately measure the mass of sludge samples, in-

Table 2. Other experimental instruments.

Experimental instruments	Model	Manufacturer
DHG	DHG-970A	Taist instrument
Box type resistance furnace	SX-4-10	Shanghai Qixin Scientific Instrument
Graphite heating plate	DB-1EFS	Shanghai Aladdin Technology Co., Ltd
Electronic balance	FA2004B	Shanghai Aladdin Technology Co., Ltd
Magnetic stirrer	-	Shanghai Jingke Tianmei Scientific Instrument

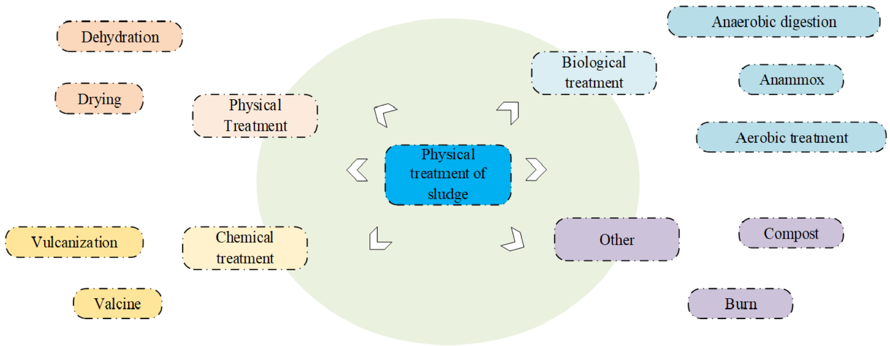


Figure 1. Schematic diagram of existing sludge treatment methods.

cluding changes in mass before and after drying. Magnetic stirrers can be used to achieve uniform mixing of sludge samples during hydrothermal reactions.

3. Basic steps for regulating sludge through hydrothermal carbonization and combined physicochemical pretreatment

Sludge treatment is a comprehensive process that involves multiple methods to cope with different environments and treatment needs. In terms of physical processing, it mainly includes two steps: dehydration and drying. Using a belt filter press or plate and frame filter press, the water in the sludge is discharged through a filter cloth or plate by applying pressure, leaving a dry solid, thereby reducing the volume and weight of the sludge and improving subsequent treatment efficiency [13, 14]. Drying utilizes microwave radiation to directly heat the water molecules in the sludge, allowing them to evaporate rapidly and achieve rapid drying, providing convenience for subsequent treatment. Chemical treatment includes two methods: calcination and vulcanization. Calcination burns organic matter in sludge under high temperature conditions of 800-1000°C. During the calcination process, inorganic substances (such as metal oxides, silicates, etc.) in the sludge undergo a series of physical and chemical reactions, partially transforming into harmless or low toxicity forms [15–17]. Sulfurization includes adding chemical reagents to react heavy metal ions in sludge with sulfides, generating stable sulfides, effectively reducing the toxicity of heavy metals, and ensuring that the treated sludge is environmentally friendly. In terms of biological treatment, anaerobic digestion, anaerobic ammonia oxidation, and aerobic treatment are commonly used methods [18, 19]. Anaerobic digestion utilizes anaerobic microorganisms to decompose organic matter in sludge. Under anaerobic conditions, anaerobic microorganisms (such as methanogens) decompose organic matter in sludge, producing gases such as methane and carbon dioxide. Under specific anaerobic conditions, anaerobic ammonia oxidizing bacteria can convert ammonia nitrogen (NH_4^+) and nitrite (NO_2^-) in sludge into nitrogen (N_2). Anaerobic ammonia oxidation converts ammonia nitrogen in sludge into nitrogen through anaerobic ammonia oxidizing bacteria, effectively reducing the pollution of ammonia nitrogen to the environment. Aerobic treatment exposes sludge to an oxygen-containing environment, utilizing aerobic microorganisms (such as bacteria, fungi, etc.) to use oxygen as an electron acceptor to degrade organic matter in sludge, further reducing volume and weight. The existing sludge treatment methods are shown in Figure 1. However, the above-mentioned sludge treatment also has corresponding drawbacks. Therefore, this study adopts a hydrothermal reaction to carbonize and regulate the sludge. Firstly, pre-treatment is carried out, where the sludge undergoes dehydration, drying, and pre pressing to remove moisture and impurities, reduce particle size, and thereby improve the carbonization of the sludge. The second step is to debug the hydrothermal reaction device, and the third step is to control the temperature and pressure between 180-250°C and 0.5-3.0 MPa. The fourth step is to adjust the hydrothermal reaction time be-

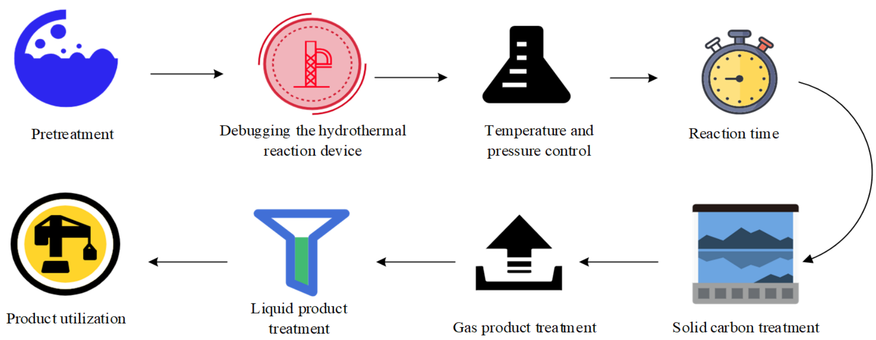


Figure 2. Basic steps for hydrothermal carbonization and conditioning of sludge through hydrothermal reaction.

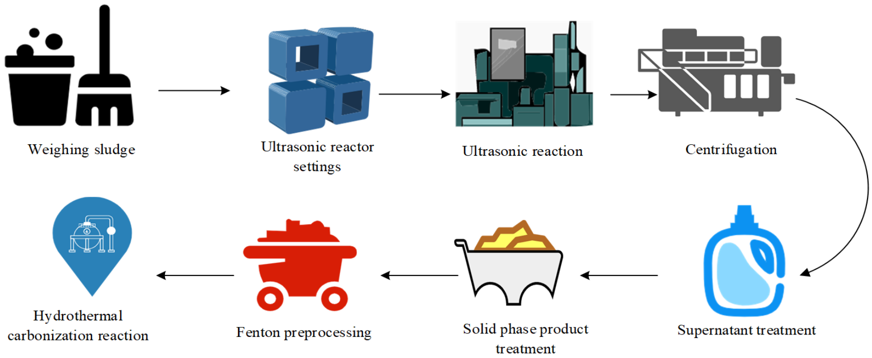


Figure 3. Wastewater treatment process using hydrothermal carbonization combined with physicochemical pretreatment.

tween 1-6 hours based on different sludge performance and treatment requirements. The fifth step is solid carbon treatment. The solid carbon produced after hydrothermal carbonization and tempering can be treated through steps such as separation, drying, and carbonization. Separation can be achieved through methods such as centrifugal separation, filtration, or pressure filtration. The sixth step is gas product treatment, and the gas products generated through hydrothermal carbonization and tempering usually include water vapor, carbon dioxide, methane, etc. These gases can be treated through technologies such as condensation, adsorption, and purification. The seventh step is to handle the liquid product. Hydrothermal carbonization and tempering also produce liquid products, including water and organic acids. These liquid products can be processed through steps such as separation, concentration, and purification, achieved through methods such as centrifugal separation, filtration, or pressure filtration. Purification can utilize technologies such as activated carbon, ion exchange resin, and membrane separation to further purify liquid products and meet environmental requirements. The eighth step is product utilization, and the product after hydrothermal carbonization and tempering treatment can be further utilized. Solid carbon can be used as a soil amendment, fuel, or adsorbent, with the basic steps shown in Figure 2. Sludge contains a large amount of water and organic pollutants, and direct hydrothermal carbonization treatment may not be effective. Through physical and chemical pretreatment, the surface structure and organic composition of sludge can be changed, thereby improving treatment efficiency without reducing the yield of hydrothermal carbon. Firstly, the sludge and distilled water are weighed, and a certain amount of sludge is weighed and added to a beaker. Distilled water is added to the beaker in a solid-liquid ratio of 1:10 [20]. Then it sets up the ultrasonic reactor, prepares the ultrasonic cleaning machine with water, and places the beaker into the cleaning machine. The third step is to perform ultrasonic reaction, adjust the power of the ultrasonic cleaning machine to 120 W, and set different ultrasonic energy densities to start the ultrasonic reaction. Further centrifugal separation is performed, placing the products in the beaker in a centrifuge and centrifuging at a speed of 5000r/min for 5 minutes. The fifth step is to treat the supernatant. After centrifugation, pour out the supernatant and store it in the refrigerator. The sixth step is solid-phase product treatment. The solid-phase product is dried in a 65°C oven, then ground, and finally collected and stored as CS. The seventh step is to perform Fenton pretreatment by mixing the sludge and hydrogen peroxide in a 1:1 mass ratio, adding an appropriate amount of $FeSO_4 \bullet 7H_2O$, and then stirring the reaction on a magnetic stirrer for a certain period of time. After the reaction is completed, the product is centrifuged and the separated supernatant and solid phase product are stored separately. Solid phase products are collected and stored as FS after cleaning, drying, and grinding. Next, the hydrothermal carbonization reaction will be carried out according to the developed hydrothermal carbonization process, as shown in Figure 3.

4. Changes in sludge characteristics under different hydrothermal reaction conditions

4.1 The impact of different raw materials

The third-generation biomass fuel uses seaweed, microalgae, and other plants with high biomass growth rates as raw materials. These plants can absorb a large amount of carbon dioxide during their growth process without causing food supply problems. In addition, the production process of third-generation biomass fuels can also utilize the oxygen generated by photosynthesis, reducing the demand for external oxygen. Therefore, third-generation biomass fuels are considered a sustainable energy alternative. It has lower carbon emissions and environmental impact. To investigate the thermogravimetric curves of different raw materials, a series of combustion experiments were conducted in this study. Among them, curve 1 represents sludge, curve 2 represents Chlorella vulgaris, and curve 3 represents a 1:1 mixture of sludge and Chlorella vulgaris. The experimental results are shown in Figure 4. Figure 4(a) shows that the TG curves of all three materials show a decreasing trend with increasing temperature. Figure 4(b) shows that the DTG curve of sludge has only one main peak, located at 320.3°C, with a peak weight loss rate of approximately 3.89% per minute. However, Chlorella vulgaris has three main peaks, with peak weight loss rates of 9.89%, 4.19%, and 4.89% per minute, respectively. When sludge is mixed with Chlorella vulgaris in a 1:1 ratio, the weight loss curve obtained is between curve 2 and curve 3, with a peak weight loss rate of approximately 5.69% per minute. Compared to ordinary

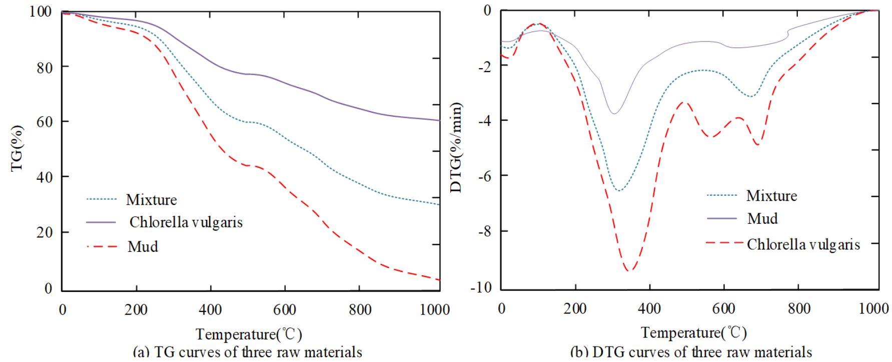


Figure 4. The influence of different raw materials on hydrothermal reactions.

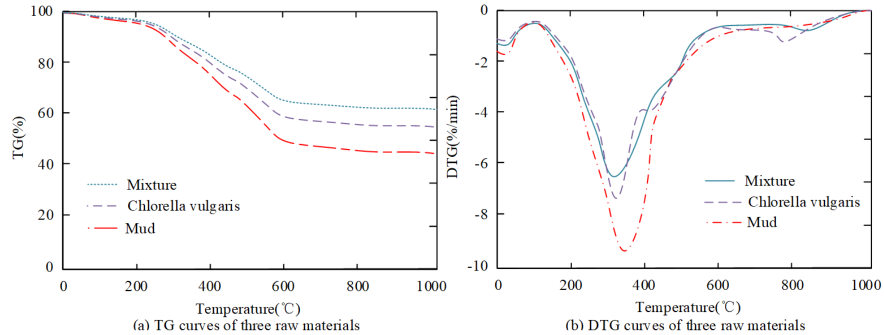


Figure 5. The influence of hydrothermal reaction temperature.

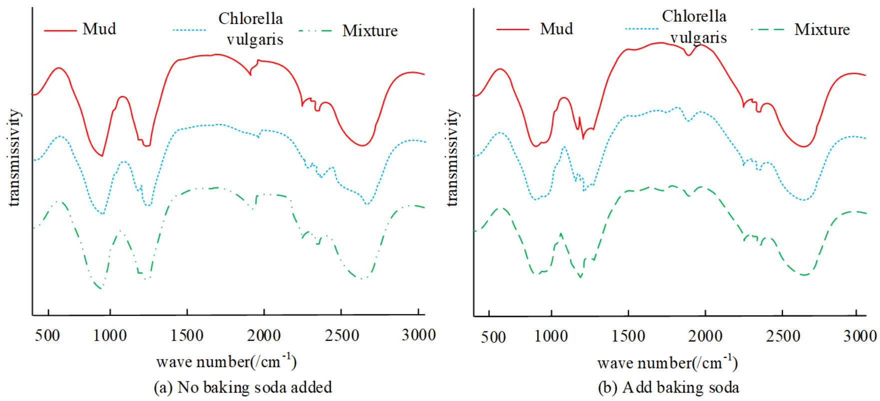
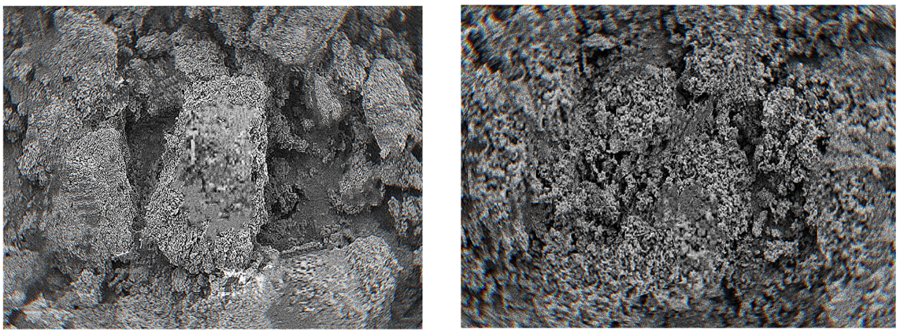


Figure 6. Effect of $NaHCO_3$ on the physicochemical properties of hydrothermal carbon.

sludge, the peak rate of weight loss per minute has increased by more than 50%, which means that participating in some third-generation biomass fuels can improve the combustion characteristics of sludge. In addition, the study also analyzed the effect of temperature on the mixture of sludge and Chlorella during the hydrothermal carbonization process, and the experimental results are shown in Figure 5. Figure 5(a) shows that the TG curves of all three curves show varying degrees of decrease with increasing temperature. As shown in Figure 5(b), under the condition of increasing the hydrothermal temperature, the maximum weight loss peak of the hydrothermal carbon was advanced to 316.6°C, and the weight loss rate also increased to 9.79%/min. At a hydrothermal reaction temperature of 150-170°, the weight loss rate curve of hydrothermal carbon is consistent with the curve of 1:1 mixing of sludge and Chlorella vulgaris, both with two main peaks. When the hydrothermal temperature rises above 190°C, the peak value increases. This indicates that as the hydrothermal reaction temperature increases, the fixed carbon content of the hydrothermal carbon decreases and the combustion residual mass ratio increases. This is because the increase in hydrothermal temperature promotes the dissolution of organic matter.

4.2 The effect of baking soda on cement hydrothermal carbonization

Exploring the influence of baking soda on the physicochemical properties of SV hydrothermal carbon can help to better understand the impact of different reaction conditions on the quality of hydrothermal carbon during the hydrother-

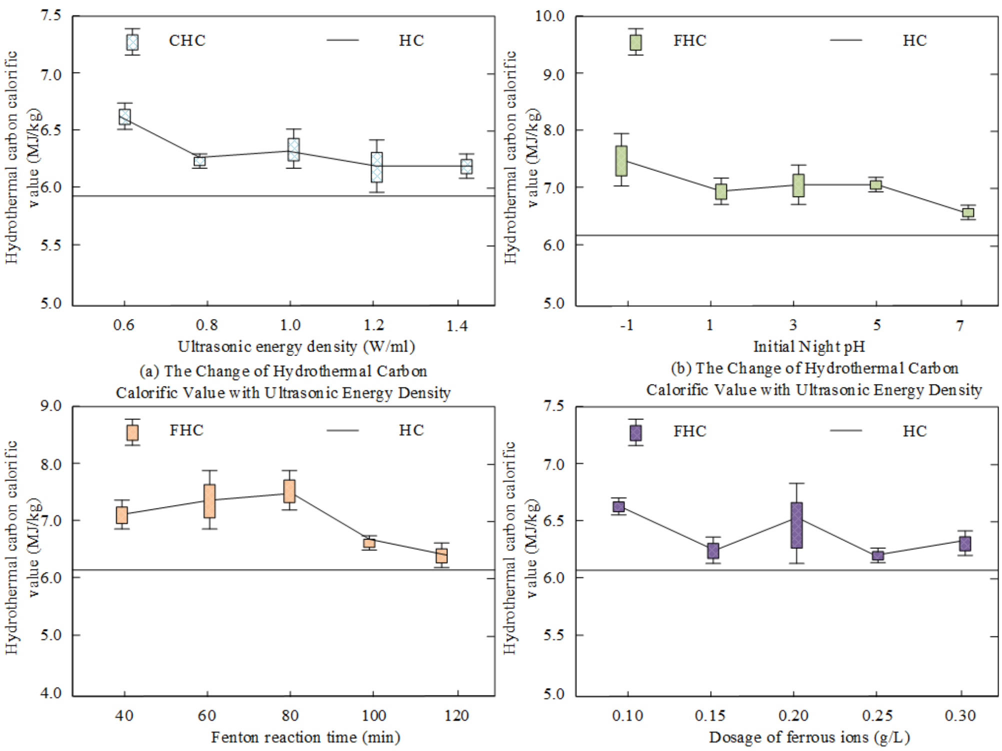


(a) Hydrothermal carbon without added baking soda

(b) Hydrothermal carbon with added baking soda

Figure 7. Effect of baking soda on hydrothermal carbon.

mal carbonization process. This provides a new method for improving the fuel quality of hydrothermal carbon. Firstly, functional group analysis was conducted in this experiment to understand the chemical composition and structure of the sludge. Then it uses infrared spectroscopy (FTIR) to observe the peaks of different functional groups, such as hydroxyl, carboxyl, ester groups, etc. This analysis result can help determine the chemical properties of sludge and further evaluate the influence of $NaHCO_3$ on the physicochemical properties of hydrothermal carbon. The experimental results are shown in Figure 6. Figure 6(a) shows that within the spectral range of 2400 cm^{-1} to 2700 cm^{-1}, it can be observed that the hydroxyl intensity of the hydrothermal carbon obtained from the three curves has decreased. Figure 6(b) shows that when adding baking soda for hydrothermal carbonization treatment, the decrease in hydroxyl groups is greater, indicating that baking soda can improve the dehydration ability of hydrothermal carbon. In addition, within the spectral range of 1000 cm^{-1} to 1500 cm^{-1}, the carbonyl intensity obtained from the three curves significantly weakened after adding baking soda. This indicates that baking soda has an impact on certain carbonyl containing compounds in hydrothermal carbon. Considering that baking soda can decompose into Na^+ and HCO_3^- in water, it may affect the conformation and stability of proteins by changing pH or interacting with other ions. Baking soda may react with certain acidic groups in hydrothermal charcoal, neutralizing the acidic environment and making proteins more easily hydrolyzed under these conditions. In summary, the addition of baking soda can enhance the de-



(a) The Change of Hydrothermal Carbon Calorific Value with Ultrasonic Energy Density

(b) The Change of Hydrothermal Carbon Calorific Value with Ultrasonic Energy Density

(c) The Change of Hydrothermal Carbon Calorific Value with Ultrasonic Energy Density

(d) The Change of Hydrothermal Carbon Calorific Value with Ultrasonic Energy Density

Figure 8. Effect of physical and chemical pretreatment on the calorific value of hydrothermal carbon.

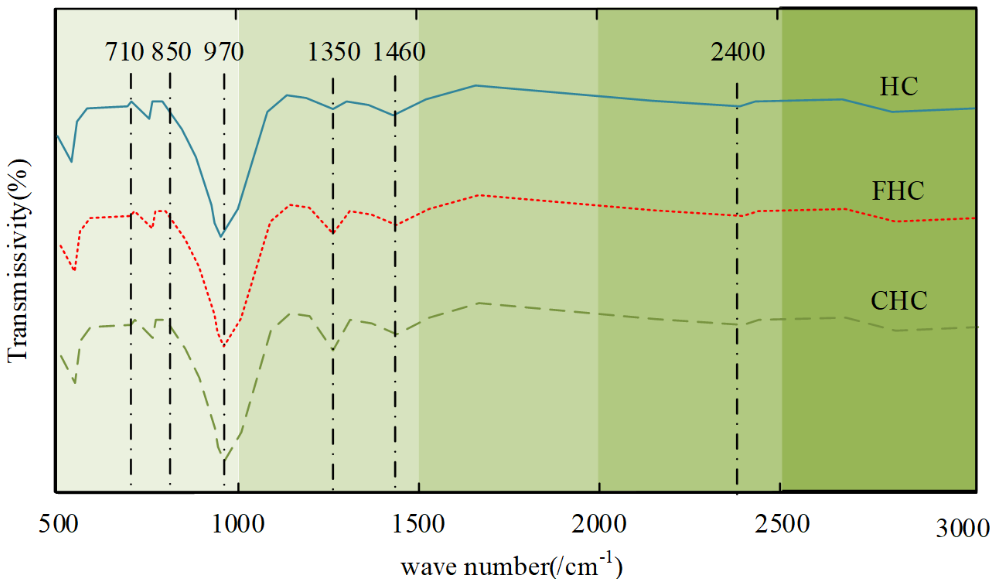


Figure 9. Effect of physicochemical pretreatment combined with hydrothermal carbonization on surface functional groups of hydrothermal carbon.

hydration ability of hydrothermal carbon and promote the protein hydrolysis process. These results have important guiding significance for the improvement and optimization of hydrothermal carbonization treatment process. To investigate the effect of different dosages of baking soda, the experiment was conducted using a scanning electron microscope, and the results are shown in Figure 7. Figure 7(a) shows that there are almost no gaps on the surface of the hydrothermal carbon of the control group without adding baking soda, and the aggregation blocks are relatively large. This shows a relatively dense structure. Figure 7(b) shows that in the experimental group with added baking soda, the surface of the hydrothermal carbon is filled with pores. The presence of these pores makes it difficult for water molecules to be retained in the matrix of hydrothermal carbon. The principle of this phenomenon is that the addition of baking soda improves the conditions for hydrothermal reactions and promotes the formation of pores in hydrothermal carbon. This increases the specific surface area, making it more difficult for water molecules to be adsorbed and retained in hydrothermal carbon.

4.3 Changes in sludge characteristics under hydrothermal carbonization combined with physicochemical pretreatment conditions

To investigate the effect of physicochemical pretreatment on the calorific value of hydrothermal carbon, comparative experiments were conducted and infrared spectroscopy analysis was performed on hydrothermal carbon. This is to investigate the effects of different ultrasonic energy densities, initial liquid pH, Fenton reaction time (min), and ferrous ion dosage (g/L) on the final hydrothermal carbon calorific value. The experimental results are shown in Figure 8. The HC calorific value in Figure 8 refers to the

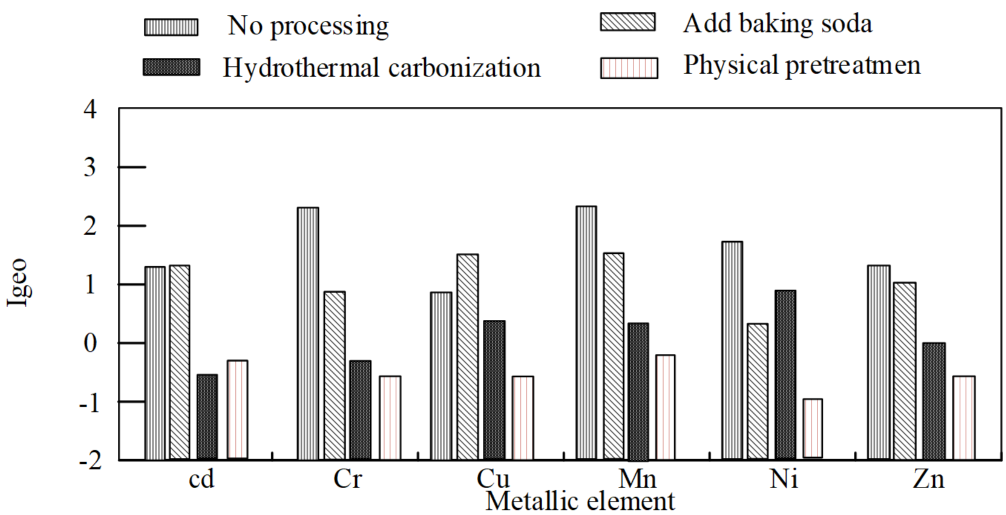


Figure 10. Various elements of different processing methods Igeo.

calorific value of untreated hydrothermal carbon. FHC calorific value refers to the calorific value of hydrothermal carbon pre treated with Fenton reagent. CHC calorific value refers to the calorific value of hydrothermal carbon after ultrasonic pretreatment. Figure 8(a) shows that the CHC calorific value generally decreases with the increase of ultrasonic energy density, with a maximum value of 6.61 MJ/kg, corresponding to a sound energy density of 0.6 W/ml. Figure 8(b) shows that the FHC calorific value shows a wave like downward trend as the initial pH of the sludge increases. When the pH reaches 7, its hydrothermal carbon calorific value is the smallest, at 6.31 MJ/kg. But it is also 3.3% higher than the calorific value of HC. Figure 8(c) shows that the overall trend of FHC calorific value increases first and then decreases with the increase of Fenton reaction time. When the reaction time reaches 80 minutes, its hydrothermal carbon calorific value reaches its maximum, which is 7.32 MJ/kg, and the HC calorific value is 19.3% higher. Figure 8(d) shows that the calorific value of FHC shows an overall unstable state with the increase of ferrous ion dosage, but the overall calorific value is at least 5% higher than that of HC. In summary, the pretreatment method has a significant impact on the calorific value and organic matter distribution of hydrothermal carbon. By selecting appropriate pretreatment methods and optimizing their parameters, the calorific value of hydrothermal carbon can be effectively increased and its performance improved. In addition, the experiment also investigated the effect of physical and chemical pretreatment combined with hydrothermal carbonization on the surface functional groups of hydrothermal carbon. The experimental results are shown in Figure 9. Figure 9 shows that the absorption peaks of HC, FHC, and CHC processes are very close. There are a total of 6 vibrations in the figure, with wave numbers of 710, 850, 970, 1350, 1460, and 2400, representing the stretching and stretching vibrations of benzene, benzene C-H, fatty amine C-N bonds, aromatic carbon, amide, ketone, and methyl C-H bonds, respectively. In addition, the figure also shows that compared with HC, the calorific value of the hydrothermal carbon pre treated with ultrasound and the hydrothermal carbon pre treated with Fenton reagent show stronger characteristic peaks at 1350 cm^{-1}. This indicates that physicochemical pretreatment promotes aromatization. Therefore, ultrasound pretreatment and Fenton reagent pretreatment play a positive role in the formation process of hydrothermal carbon. It increases the calorific value of hydrothermal carbon by promoting the occurrence of aromatization reactions.

4.4 Efficient cleaning mechanism

The research and analysis of heavy metal emissions are conducted because municipal sludge contains a certain amount of heavy metal elements. These heavy metal elements may be released into the environment during the hydrothermal carbonization and tempering process. Due to the toxicity and potential environmental risks of heavy metals, understanding and evaluating the emission of heavy metals is crucial for evaluating the feasibility and environmental impact of efficient cleaning mechanisms after hydrothermal carbonization and tempering. The experiment first used the method of three acid (HNO3-H2O2-HCL) digestion, and weighed a certain amount of material powder in a PTFE beaker. Then it is added with specific acid solution in the order of digestion and heated on a graphite heating plate. After digestion, it is fixed in a volumetric flask and measured after cooling. The cooled sample enters the atomizer through the injection capillary of ICP-OES through the action of a peristaltic pump, forming aerosols and carriers that enter the central tube of the inner layer of the quartz torch tube. This gas forms a stable "electric flame" within a quartz rectangular tube in a very short period of time. The light source enters the slit, reflector, prism, middle step grating, and collimator through a daylighting tube to form a two-dimensional spectrum, and the spectral lines fall in the form of light spots on a 512 * 512-pixel CID detector. Each spot covers several pixels, and the spectrometer measures the concentration of elements by measuring the number of photons falling on the pixels, and then analyzes the Igeo of each element separately. The experimental results are shown in Figure 10. Figure 10 shows the statistics of heavy metal content in untreated samples with the highest Igeo index for CR and Mn. While the Igeo index of the remaining elements is between the interval [1,2]. In addition, baking soda can further improve the clean combustion effect of baking soda. The Igeo index is reduced for most of the elements. However, the Igeo index of almost all elements was greatly reduced after the hydrothermal carbonization treatment, which indicates that the hydrothermal carbonization process can effectively reduce the emission of nitrogen oxides and heavy metals in the sludge. Finally, the combination of physicochemical pretreatment combined with hydrothermal carbonization had the best cleaning effect, with the Igeo of all elements reduced to pollution-free levels. Together, these treatments can effectively reduce pollutant emissions, reduce migration and toxicity of heavy metals and improve combustion efficiency. This provides new ideas and solutions for achieving efficient and clean sludge treatment.

5. Conclusion

This study investigated the effects of different hydrothermal reaction conditions on the characteristics of hydrothermal carbonization and regulated sludge through experiments, as well as the implementation mechanism of efficient cleaning mechanisms. The experimental results indicate that in the experimental group with added baking soda, the surface of hydrothermal carbon is filled with pores. The presence of these pores makes it difficult for water molecules to be retained in the matrix of hydrothermal carbon. In addition, the absorption peaks of HC, FHC, and CHC processes are very close, with 6 vibrations, namely wave numbers of 710, 850, 970, 1350, 1460, and 2400. They represent the stretching vibrations of benzene bonds, C-H bonds of benzene, C-N bonds of fatty acid amines, aromatic carbon bonds, amide bonds, ketone bonds, and methyl CH bonds, respectively. In addition, the figure also shows that compared with HC, the hot carbon pre treated by ultrasound and the hot carbon pre treated by Fenton reagent have stronger characteristic peaks at 1350 cm^{-1}. Therefore, ultrasound pretreatment and Fenton reagent pretreatment play a positive role in the formation of hydrothermal carbon. It increases the calorific value of hydrothermal carbon by promoting the occurrence of aromatization reactions. In summary, through experimental data and chart analysis, the revelation of the effective cleaning mechanism of sludge by adding additives such as baking soda and combining physical and chemical pretreatment with hydrothermal carbonization treatment has been revealed. In the future, further research can be conducted on the impact mechanism of different hydrothermal reaction conditions on the characteristics of hydrothermal carbonization and regulated sludge, as well as optimization schemes for efficient cleaning mechanisms. This provides a more scientific basis for practical applications.

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Ethical Approval

This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Authors Contributions

All authors have contributed equally to prepare the paper.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Oh C. "Exploring the Way to Harmonize Sustainable Development Assessment Methods in Article 6.2 Cooperative Approaches of the Paris Agreement". *Green and Low-Carbon Economy*, **1**:121–129, 2023.

[2] V.D. Gazman. "A New Criterion for the ESG Model". *Green and Low-Carbon Economy*, **1**:22–27, 2023.

[3] P.M. Mah, I. Skalna, T. Pełech-Pilichowski, J. Muzam, E. Munyeshuri, P.O. Uwakmfon, and P. Mudoh. "Integration of sensors and predictive analysis with machine learning as a modern tool for economic activities and a major step to fight against climate change". *Journal of Green Economy and Low-Carbon Development*, **1**:16–33, 20022.

[4] J. Huang, Z. Wang, Y. Qiao, B. Wang, Y. Yu, and M. Xu. "Transformation of nitrogen during hydrothermal carbonization of sewage sludge: Effects of temperature and Na/Ca acetates addition". *Proceedings of the Combustion Institute*, **38**:4335–4344, 2021.

[5] R.P. Ipiales, M.A. de La Rubia, E. Diaz, A.F. Mohedano, and J.J.L. Rodriguez. "Integration of hydrothermal carbonization and anaerobic digestion for energy recovery of biomass waste: An overview". *Energy and Fuels*, **35**:17032–17050, 2021.

[6] N.M.Y Almahbashi, Kutty S.R.M, and Ayoub M. "Optimization of preparation conditions of sewage sludge based activated carbon". *Ain Shams Engineering Journal*, **12**:1175–1182, 2021.

[7] Li L.Y. Mohamed, B.A. nad. "Biofuel production by co-pyrolysis of sewage sludge and other materials: a review". *Environmental Chemistry Letters*, **21**:153–182, 2023.

[8] K. Hui, J. Tang, H. Lu, B. **, C. Qu, and J. Li. "Status and prospect of oil recovery from oily sludge: A review". *Arabian Journal Of Chemistry*, **13**:6523–6543, 2020.

[9] O.S. Djandja, Z.C. Wang, F. Wang, Y.P. Xu, and P.G. Duan. "Pyrolysis of municipal sewage sludge for biofuel production: a review". *Industrial and Engineering Chemistry Research*, **59**:16939–16956, 2020.

[10] T. Luo, Q. Xu, W. Wei, J. Sun, X. Dai, and B.J. Ni. "Performance and mechanism of Fe3O4 improving biotransformation of waste activated sludge into liquid high-value products". *Environmental Science and Technology*, **56**:3658–3668, 2022.

[11] M.C. Benalia, L. Youcef, M.G. Bouaziz, S. Achour, and H Menasra. "Removal of heavy metals from industrial wastewater by chemical precipitation: mechanisms and sludge characterization". *Arabian Journal for Science and Engineering*, **47**:5587–5599, 2022.

[12] Y. Wang, W. Wei, and Wu S.L. "Zerovalent iron effectively enhances medium-chain fatty acids production from waste activated sludge through improving sludge biodegradability and electron transfer efficiency". *Environmental Science and Technology*, **54**: 10904–10915, 2020.

[13] W. Wei, Q.S. Huang, J. Sun, X. Dai, and B.J. Ni. "Revealing the mechanisms of polyethylene microplastics affecting anaerobic digestion of waste activated sludge". *Environmental Science and Technology*, **53**: 9604–9613, 2019.

[14] D.T.K. Ho. "Abundance of microplastics in wastewater treatment sludge". *Journal of Human, Earth, and Future*, **3**:138–146, 2022.

[15] Y. Liu, R. Lin, Y. Man, and J. Ren. "Recent developments of hydrogen production from sewage sludge by biological and thermochemical process". *International Journal of Hydrogen Energy*, **44**:19676–19697, 2019.

[16] A.E. Oluwalana and P.A. Ajibade. "Structural, optical and photocatalytic studies of hexadecylamine-capped lead sulfide nanoparticles". *International Journal of Industrial Chemistry*, **11**:249–260, 2020.

[17] X.D. Li and Q.Z. Zhai. "Evaluation of eosin Y removal from aqueous solution using nano-mesoporous material MCFs: adsorption equilibrium, kinetics, and adsorption isotherms". *International Journal of Industrial Chemistry*, **11**:55–67, 2020.

[18] Y. Zhang, Z. Wan, L. Wang, B. Guo, B. Ma, L. Chen, and D.C. Tsang. "Designing magnesium phosphate cement for stabilization/solidification of Zn-rich electroplating sludge". *Environmental Science and Technology*, **56**:9398–9407, 2022.

[19] B. Wu, S.M. Berg, C.K. Remucal, and T.J. Strathmann. "Evolution of N-containing compounds during hydrothermal liquefaction of sewage sludge". *ACS Sustainable Chemistry and Engineering*, **8**:18303–18313, 2020.

[20] M. Qi, B. Liang, L. Zhang, X. Ma, L. Yan, W. ... Dong, and A. Wang. "Microbial interactions drive the complete catabolism of the antibiotic sulfamethoxazole in activated sludge microbiomes". *Environmental Science and Technology*, **55**:3270–3282, 2021.