The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Optimization and Modeling of Retention Time and Temperature Parameters in the Hydrothermal Carbonization Process of Sewage Sludge

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Article Info

Article type:
Research Article

Article history:
Received: 2 October 2024
Revised: 28 November 2024
Accepted: 17 January 2025

Keywords:
Hydrothermal Carbonization
Hydrochar Yield
Energy Yield
Response Surface Method

ABSTRACT

The sustainable management of wastewater treatment plant sludge is a significant challenge in urban waste management. Hydrothermal carbonization (HTC) offers a promising approach by converting sludge into valuable products like hydrochar. This study hypothesized that optimizing HTC parameters could enhance hydrochar production while improving energy recovery. The objectives were to model and optimize the effects of temperature (150-250 °C) and retention time (20-60 min) on hydrochar yield (HY), higher heating value (HHV), and energy yield (EY). Using the Response Surface Methodology with Central Composite Design, three quadratic models were developed to analyze these parameters' interactions and identify optimal process conditions. Experimental results indicated maximum HY (59.96%) at 160.31 °C and 28.14 min, maximum HHV (26.88 MJ/kg) at 246.45 °C and 60 min, and maximum EY (82.18%) at 207.78 °C and 34.28 min. These findings highlight HTC's potential for efficient sludge management. Future research could focus on the environmental implications and scaling HTC technology for broader applications.

Cite this article: Ghasemzadeh, R., Pazoki, A., Tajziehchi, S., Ahmadi, S., & Davami, A. (2025). Optimization and Modeling of Retention Time and Temperature Parameters in the Hydrothermal Carbonization Process of Sewage Sludge . *Pollution*, 11(2), 538-549.
https://doi.org/10.22059/poll.2024.383262.2587

DOI: https://doi.org/10.22059/poll.2024.383262.2587

INTRODUCTION

The worldwide growth in population and urbanization has resulted in a substantial increase in the generation of sewage sludge (SS), an aadditional by-product of sewage treatment plants (Pazoki et al., 2020). At the same time, the swift exhaustion of worldwide fossil fuel supplies and the environmental damage and greenhouse gas emissions resulting from burning fossil fuels have underscored the unsustainable nature of conventional fossil fuel-based energy systems. Consequently, identifying appropriate renewable energy substitutes to supplant fossil fuels has emerged as a critical imperative for restructuring the energy landscape to meet global sustainability objectives (Maleki Delarestaghi et al., 2018; Pazoki et al., 2018; Wang et al., 2022). There is a growing emphasis on promoting environmental sustainability, particularly in developing countries. Lately, there has been a growing emphasis on the sustainable handling of organic waste, acknowledging its potential to tackle environmental and resource-related challenges effectively (Adeniyi et al., 2022; Amenyeku et al., 2024; Pazoki et al., 2018).

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Hydrothermal carbonization (HTC) is emerging as a promising technology for treating wet organic solid waste, capable of transforming such waste (e.g., sludge) into valuable hydrothermal charcoal, fuel, and organic products (Lynam et al., 2011; Reza et al., 2013; Zheng et al., 2022). Water plays a crucial role in HTC by initiating and enhancing the carbonization process (Nizamuddin et al., 2016;Pauline et al., 2020). Nevertheless, the conventional utilization of water in HTC processes escalates operational expenses and adversely affects environmental sustainability. HTC necessitates significant quantities of water as tFhe reaction medium, frequently employing distilled or deionized water, thereby compromising the process's environmental sustainability (Abdoli et al., 2024; Nizamuddin et al., 2015; Pauline et al., 2020). HTC offers several environmental benefits compared to traditional sludge management techniques such as incineration or landfilling. HTC reduces the volume of sludge, stabilizes organic content, and produces hydrochar, which can be utilized as a solid fuel or soil amendment, thus promoting resource recovery. Unlike incineration, HTC operates at lower temperatures, minimizing air pollutant emissions. Additionally, compared to landfilling, HTC mitigates greenhouse gas emissions by preventing methane generation. A brief discussion on these potential environmental advantages has been added to the manuscript to emphasize the significance of HTC as a sustainable waste management approach (Fakudze et al., 2023; Guo et al., 2024; Yan et al., 2023).

Temperature plays a pivotal role in the hydrothermal carbonization (HTC) process, significantly influencing the quality and properties of the hydrochar produced. Studies show that increasing temperatures from around 150°C to 250°C enhances carbonization, resulting in hydrochar with a higher carbon content and energy density (Reza et al., 2014). Reza et al. (2014) demonstrated that temperatures above 200°C led to a notable reduction in oxygen content, improving fuel properties (Reza et al., 2014). Conversely, Kruse et al. (2013) highlighted that excessively high temperatures can decrease solid yields by favoring gasification or liquefaction, emphasizing the need to balance yield and energy density. Additionally, higher temperatures accelerate reaction kinetics, allowing for shorter retention times, which further underscores the importance of temperature optimization in HTC processes (Kruse et al., 2013).

Retention time is equally crucial, with longer durations generally leading to improved carbonization and hydrochar quality. Parshetti et al. (2013) found that extending retention time from 30 to 60 minutes at 200°C significantly enhanced carbon content and stability (Parshetti et al., 2013). However, the relationship between retention time and temperature is critical, as Kruse et al. (2013) noted that higher temperatures can reduce the required retention time for effective biomass conversion (Kruse et al., 2013). Other factors, such as pH, feedstock type, pressure, and the solid-liquid ratio, also significantly impact the HTC process. Liu et al. (2012 indicated that mildly acidic conditions improve hydrochar quality, while Lu et al. (2020) demonstrated that co-hydrothermal carbonization of sewage sludge with food waste produced hydrochar with enhanced energy properties. Collectively, these studies highlight the complex interplay of parameters in optimizing the HTC process for high-quality hydrochar production (Liu et al., 2012; Lu et al., 2021). A wealth of research has been conducted on HTC involving a wide range of biomass feedstocks, among which SS has been extensively studied. However, most of these studies primarily focus on the characterization of hydrochar and its thermal behavior (Ghasemzadeh et al., 2022; Hämäläinen et al., 2021).

In summary, the parameters governing the HTC process have a direct impact on both the yield of hydrochar (HY) and the fuel quality of hydrochar, as well as on the methane production potential of HTC wastewater. Nevertheless, existing research has predominantly concentrated on optimizing and improving the characteristics of solid-phase hydrochar. For instance, Zhang et al. conducted experiments focusing on individual factors to investigate the fuel properties of wheat straw hydrochar across a range of HTC temperatures and residence times. Their findings indicated that by intensifying the HTC reaction, the higher heating value (HHV) of hydrochar could be increased significantly, from 19.61 to 27.90 MJ/kg (Zhang et al., 2020). Other researchers have reported similar findings, noting that the increase in HHV due to extended HTC residence time and elevated temperature was constrained under high concentration conditions (Sabio et al., 2016; Álvarez-Murillo et al., 2015). Also, Akbari et al researched on evaluating optimized conditions include of temperature, retention time, and biomass:water ratio. They included that effect of biomass:water ratio was biomass:water ratio and on the other hand, the effect of temperature and retention time on outputs including HY, HHV, and EY is more effective. Therefore, it is necessary to conduct a more complete study on the effect of temperature and retention time on HTC of SS (Akbari et al., 2022). Also, there is a significant lack of comprehensive studies exploring the synergistic impacts of different HTC conditions on the material and EY performance, particularly in the context of SS. This gap is especially evident in terms of optimizing energy recovery through an integrated HTC process for treating SS and other biomass. This study aims to bridge this gap by introducing an innovative method for converting organic wastes into renewable energy sources while ensuring clean and efficient utilization.

This study investigates the influence of key hydrothermal conditions, specifically temperature and retention time, on parameters such as HY, HHV, and EY in the HTC process of SS. As the first research to thoroughly examine the simultaneous effects of these variables, the focus is on determining how these factors interact and optimizing their influence on the HTC process. Using response surface methodology (RSM), the research assesses the impact of temperature (150–250°C) and retention time (20–60 minutes) to identify the optimal conditions for HTC treatment of SS. In addition to analyzing the process' effects on HY, HHV, and EY, this study aims to identify the types and roles of effective parameters, evaluating their individual and combined effects on the efficiency of the HTC process. The optimization of these parameters, particularly to enhance the energy recovery from SS, is a key objective of this work.

MATERIALS AND METHODS

Sampling and analysis of SS

Samples of SS were sourced from the municipal wastewater treatment plant (WWTP) located in Tehran, Iran. The initial samples displayed an 80% moisture content and had a pH of 6.11. Following collection, they were kept in a plastic container at 4°C for later use. To ensure homogeneity, the SS was triturated, sieved through a #60 mesh, and thoroughly mixed. The HHV of the SS was measured to be 16.8 MJ/kg.

HTC process

The HTC experiments employed a stainless-steel batch-mode reactor, with a working volume of 2 liters, featuring a pressure gage and temperature controller. Each trial began by introducing a specific quantity of SS sample and 1.8 liters of distilled water, adhering to the experimental protocol. The reactor was sealed, and temperature increased gradually at approximately 15 °C per minute until reaching the desired experimental temperature. Upon reaching the target temperature (designed), the reactor maintained it for the prescribed retention time outlined in the experimental plan. To ensure reliability, all experiments were conducted in triplicate. Upon completion of each HTC test, the reactor underwent controlled cooling to return to 25 °C. The resultant hydrochar and liquid fraction were separated using 6 μm pore size filter paper. The separated hydrochar was subsequently dried at 105 °C for 24 hours and stored in a plastic bag at 4 °C for future analyses. HY for each experiment was quantified using a specified equation.

A microcomputer automated calorimeter (ZDHW-9000C) was employed to measure the HHV of both raw SS and the produced hydrochars. The equations used to estimate the EY and HY for each test are as follows:

$$\mathrm{HY}\,(\%) = \left(\frac{\text{Hydrochar Dry Mass}\,(\mathrm{g})}{\text{SS Dry Mass}\,(\mathrm{g})}\right)\times 100 \tag{1}$$

$$\mathrm{EY}\,(\%) = \text{Hydrochar yield}\times\left(\frac{\text{Higher heating value of hydrochar}}{\text{Higher heating value of SS}}\right) \tag{2}$$

Experimental design and analysis

This study employed the Central Composite Design (CCD) within the framework of RSM to evaluate the effects of independent variables and optimize system performance for specific responses, as outlined by Akbari et al. (2022). CCD systematically fits models using the least squares method and explores interactions between parameters to understand their impact on responses. Specifically, a two-level, two-factor CCD was utilized, encompassing 13 experimental runs with five replicates at the central point.

The independent variables in this study were temperature (x1) and retention time (x2). Temperature levels were coded as -1, 0, and +1, corresponding to 150, 200, and 250 °C, respectively. Retention time levels were coded as -1, 0, and +1, corresponding to 20, 40, and 60 minutes, respectively.

As per equation (3), the connection between the factors and the response is represented by a quadratic equation.

$$Y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n}\sum_{j>2}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2 + e \tag{3}$$

Within this framework, Y signifies the predicted outcome, where b0 stands for the constant term. The term bij signifies the interaction coefficients between factors i and j, while bi indicates the linear coefficients of individual factors. Additionally, bij signifies the quadratic coefficients of the variables. In this context, Xi and Xj denote the coded values assigned to independent variables i and j, respectively, while *e* denotes the random error inherent in the model. The experiment was designed, regression analysis was conducted, and the response surface was mapped using the Design Expert (DE) program (Version 13). Table 1 presents the CCD matrix for evaluating HY, HHV, and EY under HTC conditions.

Table 1. Experimental design matrix and the corresponding response results

Run	Std	Coded level		Actual level of variables		HY, Y1 (%)	HHV, Y2 (Mj/kg)	EY, Y3 (%)
		X_1	X_2	X_1 (°C)	X_2 (min)			
1	11	0	0	200	40	56.14	23.78	79.18
2	7	0	-1.414	200	11.72	59.17	21.26	75.19
3	10	0	0	200	40	57.63	24.92	83.76
4	9	0	0	200	40	56.59	24.6	81.26
5	8	0	1.414	200	68.28	43.29	24.87	63.45
6	1	-1	-1	150	20	59.48	18.78	66.98
7	6	1.414	0	270.71	40	45.18	23.95	63.34
8	12	0	0	200	40	54.97	24.26	82.14
9	5	-1.414	0	129.29	40	56.91	15.56	53.94
10	13	0	0	200	40	55.79	23.92	78.95
11	4	1	2	250	60	42.19	27.09	65.31
12	2	1	-1	250	20	51.78	22.76	69.29
13	3	-1	1	150	60	48.12	19.12	54.34

RESULTS AND DISCUSSION

The DE software was employed to optimize the HTC process through a series of experiments. The study focused on process reaction time and temperature as the main operational factors to enhance the HY. Table 2 provides an analysis of the experimental data using DE and analysis of variance (ANOVA). The reliability of the regression model was assessed through probability (p-value) and Fisher (F) test values. According to Abdoli et al. (2024), models with lower p-values and higher F values are considered more reliable indicators (Abdoli et al., 2024). In this study, significant F values of 97.23, 113.13, and 54.91 were observed for HY, higher HHV, and EY, respectively, with all p-values below 0.0001, affirming the significance of the models (Tables 2-4).

The examination of R^2 and adjusted R^2 values took into account several factors relative to the dataset size. Specifically, for the HY model, the R^2 value of 98.58% illustrates a compelling correlation between the predicted and experimental values, as depicted in Figure 1(a). Likewise,

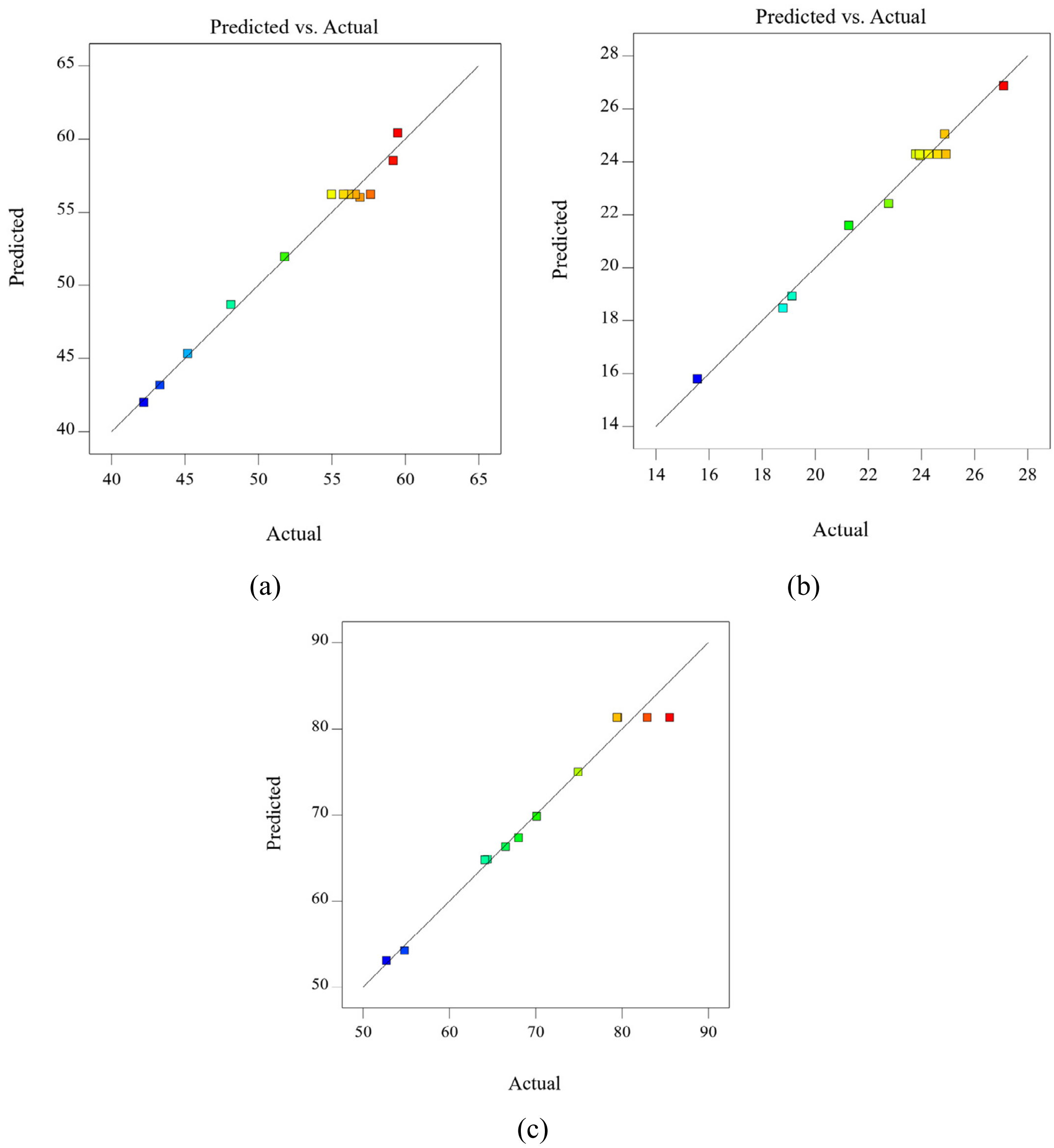

Fig. 1. Correlation between actual and predicted values of (a) HY, (b) HHV and (c) EY

Table 2. ANOVA for HY modeling and optimization in HTC of SS

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value	Remarks
Model	442.19	5	88.44	97.23	<0.0001	Significant
X_1- Temperature	114.15	1	114.15	125.49	<0.0001	
X_2- Retention time	235.53	1	235.53	258.94	<0.0001	
X_1X_2	0.7832	1	0.7832	0.8611	0.3843	
X_1^2	53.60	1	53.60	58.93	0.0001	
X_2^2	50.09	1	50.09	55.06	0.0001	
Residual	6.37	7	09.96			
Lack of fit	2.49	3	0.8295	0.8554	0.5324	Not significant
Pure error	3.88	4	0.9697			
Correlation total	448.55	12				

the HHV model exhibited R^2 values of 98.78%. The strong agreement between theoretical and experimental HY values underscores the effectiveness of the developed model in capturing the relationships among HTC variables and HY, HHV, and EY. Additionally, the adjusted R^2 values were 97.57% for HY, 97.9% for HHV, and 97.78% for EY, highlighting the model's capability to robustly consider the influence of independent variables. These elevated R^2 and adjusted R^2 values indicate a strong fit of the model to the experimental data.

In this context, A refers to the actual temperature value, and B refers to the actual retention time. The responses measured included HY, HHV, and EY. The impact of a single variable is denoted by a one-factor coefficient, whereas interactions between two variables are expressed through two-factor coefficients. Synergistic effects are indicated by positive signs, while antagonistic effects are indicated by negative signs.

Impact of Various Parameters on HY

The normal plots (Fig. 1) for HY, HHV, and EY were used to assess the experimental errors before analyzing the specific data. Specifically, the points in plots in Fig. 1 aligned along a straight line, demonstrating that the residuals are normally distributed, which confirms their normality for all responses (Anupam et al., 2016; Tajfar et al., 2023).

The HY varied between 42.19% and 59.48%, with the minimum and maximum values observed in Run 4 (150 °C for 30 minutes) and Run 1 (200 °C for 30 minutes), respectively. The model for HY (%) based on actual components is given in Equation 4:

$$HY = +30.58 + 0.35\ A + 0.18\ B + 0.0004\ AB - 0.001\ A^2 - 0.007\ B^2 \quad (4)$$

Equation 4 models HY as a function of temperature (A) and retention time (B), derived using RSM-CCD. The linear terms (+0.35 A and +0.18 B) show the direct influence of temperature and retention time, while the interaction term (+0.0004 AB) accounts for their combined effect. The quadratic terms (−0.001A2 and −0.007 B2) reflect how deviations from optimal values reduce HY. This model, based on coded factors, allows accurate prediction of responses across various conditions and supports optimization by minimizing experimental efforts, making it a valuable tool in hydrothermal carbonization research. Table 2 displays the results of the HY ANOVA. Retention time and temperature demonstrate notable impacts on HY (p-values below 0.05). Specifically, temperature was found to exert a more significant effect than retention time, with p-values of 0.0009 and 0.002, respectively.

Fig. 2 depicts the response surface plot of HY and can be directly examined. The plot illustrates that HY decreases with increasing temperature and shows a lesser decrease with increasing retention time. This trend indicates that as the carbonization temperature rises, more of the biomass constituents undergo degradation, resulting in a reduction in HY (Heidary, 2017; Sabio et al., 2016). In the context of SS, the reduction in char yield as temperature increases may

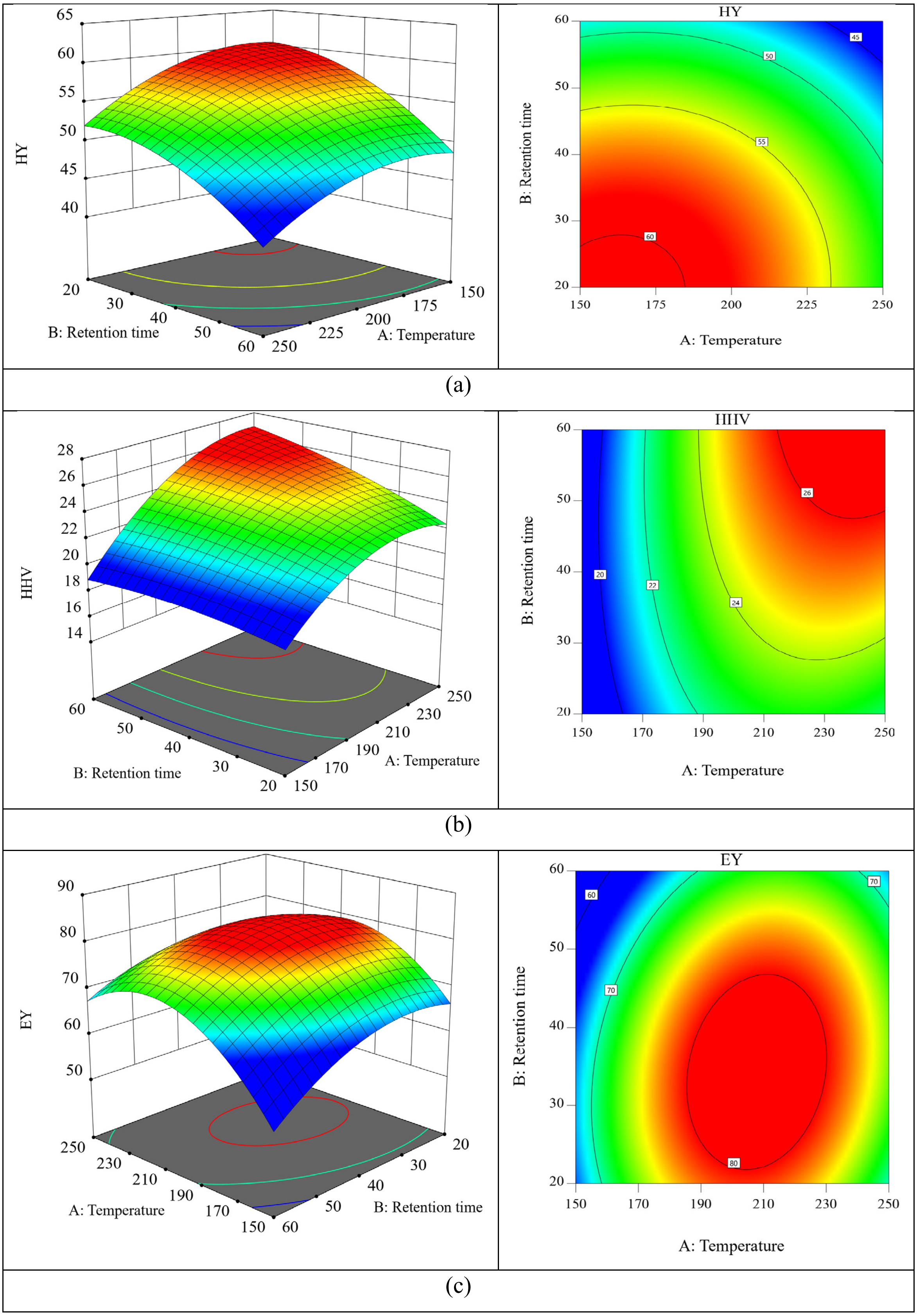

Fig. 2. Impact of retention time and temperature on (a) HY, (b) HHV, and (c) EY analyzed through three-dimensional response surface analysis

be attributed to the weakening of the hydrogen bonding network within the molecular cellulose matrix. This phenomenon, more pronounced at temperatures above 190 °C, involves the polar CH_2OH groups acting as "molecular radiators," leading to cleavage of the polysaccharide chain and the generation of glucose (Sabio et al., 2016).

Impact of Various Parameters on HHV

The HHV is a vital attribute of hydrochar, particularly for fuel applications, as a higher HHV improves combustion efficiency and enables more economical transportation. The equation representing the hydrochar HHV (MJ/kg) in terms of actual variables is presented by Equation (5):

$$HHV = -18.23 + 0.36\ A - 0.042\ B + 0.001\ AB - 0.001\ A^2 - 0.001\ B^2 \quad (5)$$

Table 3 shows that the HHVs of the produced hydrochars were significantly affected by all tested factors, as indicated by the ANOVA results. The p-values demonstrate that temperature had a more pronounced influence than retention time. The 3-dimensional response surface plot of hydrochars HHVs is illustrated in Fig. 2. Increasing retention time and temperature caused the HHV of the hydrochar to increase. These findings align with previous studies (Kang et al., 2019; Tag et al., 2018). Enhancing both the retention time and temperature led to a greater concentration of carbon in the hydrochar. Additionally, decarboxylation and dehydration occur at higher temperatures, decreasing the atomic ratios of H/C and O/C. The oxygen concentration in the hydrochar is reduced by decarboxylation. As a result of these processes, the hydrochar's HHV was enhanced (Kannan et al., 2017). In all the results, the hydrochar's HHV was increased compared to the starting SS.

Impact of Various Parameters on EY

Eq. 2 defines the EY as a comprehensive measure that incorporates both the HHV and HY, indicating the total energy retained in the hydrochar from the raw biomass. The model for HY (%) based on actual factors is given in Equation (6):

$$EY = -110.74 + 1.78\ A + 0.48\ B + 0.002\ AB - 0.004\ A^2 - 0.014\ B^2 \quad (6)$$

Table 4 presents the ANOVA results for EY. The analysis shows that retention time (p-value = 0.0002 ≤ 0.05) and temperature (p-value = 0.0009 ≤ 0.05) were the most significant factors affecting energy output. Fig. 2 illustrates that optimal energy production was attained at moderate temperatures and retention times. These conditions reflect the differing trends of HHV and HY

Table 3. ANOVA for HHV modeling and optimization in HTC of SS

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value	Remarks
Model	118.93	5	23.79	113.13	<0.0001	Significant
X_1- Temperature	70.90	1	70.90	337.18	<0.0001	
X_2- Retention time	11.94	1	11.94	56.81	0.0001	
X_1X_2	3.98	1	3.98	18.93	0.0034	
X_1^2	31.82	1	31.82	151.32	<0.0001	
X_2^2	1.63	1	1.63	7.74	0.0272	
Residual	1.47	7	0.2103			
Lack of fit	0.5811	3	0.1937	0.5267	0.5267	Not significant
Pure error	0.8907	4	0.2227			
Correlation total	120.41	12				

Table 4. ANOVA for EY modeling and optimization in HTC of SS

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value	Remarks
Model	1266.66	5	253.33	54.91	<0.0001	Significant
X_1- Temperature	139.00	1	139.00	30.13	0.0009	
X_2- Retention time	105.66	1	105.66	22.90	0.0020	
X_1X_2	23.04	1	23.04	4.99	0.0605	
X_1^2	870.87	1	870.87	188.78	<0.0001	
X_2^2	227.11	1	227.11	49.23	0.0002	
Residual	32.29	7	4.61			
Lack of fit	1.64	3	0.5469	0.0714	0.9722	Not significant
Pure error	30.65	4	7.66			
Correlation total	1298.95	12				

in response to changes in reaction conditions. Lower HTC temperatures resulted in higher HY but lower HHV. In contrast, higher HTC temperatures led to decreased hydrochar production while significantly increasing HHV. This phenomenon is attributed to higher temperatures, which facilitate the complete breakdown of the woody-cellulosic structure and enhance carbon enrichment in the hydrochar. Consequently, the biomass matrix undergoes thorough decomposition, producing less hydrochar with a higher HHV. Once a specific threshold for temperature and retention time is surpassed, there is adequate energy to initiate a thorough decomposition of the SS structure, removing oxygen-containing groups and resulting in less hydrochar with higher HHV. Furthermore, temperature exhibited a more pronounced effect on EY compared to retention time, as evidenced by the higher F-value for temperature in the ANOVA analysis.

Optimization of effective parameters on HY, HHV, and EY

The optimal reaction conditions for maximizing EY, HHV, and HY were identified using the optimization tool integrated into the DE program. Table 5 illustrated the optimal conditions for each target. The highest HY, HHV, and EY were attained at 59.96% (achieved at 160.31 °C and 28.14 minutes), 26.88 MJ/kg (reached at 246.45 °C and 60 minutes), and 82.18% (obtained at 207.78 °C and 34.28 minutes), respectively. Notably, energy consumption was not considered in calculating EY, as this metric primarily evaluates the hydrochar's quality.

HTC tests on SS conducted in laboratory settings are subject to several limitations. One major constraint is scalability, as the behavior of lab-scale systems often differs from larger, industrial-scale operations due to variations in heat transfer, mixing, and residence times. Additionally, the heterogeneity of sewage sludge is often underrepresented in lab studies, where uniform samples may limit the broader applicability of the results. The controlled environment of laboratory experiments, with precise temperature, pressure, and pH, may not accurately replicate real-world conditions, leading to potential discrepancies in process performance. Moreover, the restricted range of operational parameters and shorter experimental durations may result in suboptimal assessments of process efficiency and hydrochar quality. Energy consumption, a critical factor for evaluating overall process efficiency, is frequently overlooked in lab settings. The variability in sewage sludge composition across different locations and seasons further complicates generalization of findings. Environmental impacts of byproducts and potential emissions are also often inadequately captured in laboratory-scale experiments. Finally, the economic feasibility of scaling the HTC process, including operational costs and hydrochar marketability, is typically not addressed, posing challenges for industrial applications.

Table 5. HTC optimal conditions and predicted of the responses

	Optimal Operating Conditions		Predicted Response			
Variables	Temperature (°C)	Retention time (min)	HY (%)	HHV (MJ/kg) p	EY (%)	Desirability
Goal	In Range	In Range	Maximize	-	-	-
	160.31	28.14	59.96	20.16	72.25	1
Goal	In Range	In Range	-	Maximize	-	-
	246.45	60	42.62	26.88	68.44	0.982
Goal	In Range	In Range	-	-	Maximize	-
	207.78	34.28	56.88	24.27	82.18	0.899

CONCLUSION

This study presents the modeling and optimization of HY, HHV, and EY through the HTC of SS, considering optimal conditions and operational parameters such as retention time and temperature. The findings indicate that the HTC process exhibited high efficiency, with HY and HHV showing greater sensitivity to reaction temperature compared to retention time. The study successfully identified the optimal conditions for maximizing each target output, with the highest HY of 59.96% achieved at an optimal temperature of 160.31 °C and a retention time of 28.14 minutes. The maximum HHV of 26.88 MJ/kg was reached at 246.45 °C and 60 minutes, while the optimal EY of 82.18% was obtained at 207.78 °C and 34.28 minutes. Achieving these optimal conditions is crucial for maximizing the effectiveness of the HTC process. Importantly, energy consumption was excluded from the evaluation of energy yield, emphasizing that the focus is on assessing the quality of the hydrochar produced. Factors such as the amount of water, pH conditions, and type of reactor likely influence the process. This study enhances the theoretical understanding of the hydrothermal carbonization process for wastewater treatment plant sludge by optimizing key parameters such as temperature and retention time. The findings highlight the potential of hydrothermal carbonization as a sustainable waste-to-energy solution, demonstrating that careful adjustment of these parameters can significantly improve energy yield, higher heating value, and hydrochar yield. Practically, the results provide a valuable framework for optimizing the process, which can be applied to urban waste management systems to promote efficient energy recovery and environmentally friendly sludge treatment. The research emphasizes the importance of modeling techniques in identifying optimal conditions and underscores the role of hydrothermal carbonization in advancing waste-to-energy technologies. Suggestions for future studies include research on other parameters such as concentration, pH, and the addition of various catalysts. Additionally, other types of waste, such as municipal, industrial, and agricultural waste that contain organic components, can be considered as potential feedstock for the hydrothermal carbonization process. Furthermore, the hydrothermal carbonization process can be conducted under different temperature and time conditions, or hydrothermal liquefaction and hydrothermal gasification processes can also be utilized.

ACKNOWLEDGEMENT

We express our gratitude to the Waste to Energy Lab in University of Tehran for their generous assistance, direction, and insightful advice.

GRANT SUPPORT DETAILS

No financial assistance was provided for this research.

CONFLICT OF INTEREST

The authors confirm that there are no conflicts of interest regarding the publication of this manuscript. Additionally, the authors have strictly adhered to ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, duplicate publication and/or submission, and redundancy.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Abdoli, M. A., & Ghasemzadeh, R. (2024). Evaluation and optimization of hydrothermal carbonization condition for hydrochar and methane yield from anaerobic digestion of organic fraction of municipal solid waste (OFMSW). *Fuel*, *355*, 129531.

Adeniyi, A. G., Adeyanju, C. A., Emenike, E. C., Otoikhian, S. K., Ogunniyi, S., Iwuozor, K. O., & Raji, A. A. (2022). Thermal energy recovery and valorisation of Delonix regia stem for biochar production. *Environmental Challenges*, *9*, 100630.

Álvarez-Murillo, A., Román, S., Ledesma, B., & Sabio, E. (2015). Study of variables in energy densification of olive stone by hydrothermal carbonization. *Journal of Analytical and Applied Pyrolysis*, *113*, 307–314.

Amenyeku, G., Cobbina, S. J., Asare, W., & Teye, G. K. (2024). Hydrothermal carbonization of organic waste using faecal sludge as a water source: Response surface methodology-Box Behnken design. *Environmental Challenges*, *15*, 100900.

Anupam, K., Sharma, A. K., Lal, P. S., Dutta, S., & Maity, S. (2016). Preparation, characterization and optimization for upgrading Leucaena leucocephala bark to biochar fuel with high energy yielding. *Energy*, *106*, 743–756.

Fakudze, S., & Chen, J. (2023). A critical review on co-hydrothermal carbonization of biomass and fossil-based feedstocks for cleaner solid fuel production: Synergistic effects and environmental benefits. *Chemical Engineering Journal*, *457*, 141004.

Ghasemzadeh, R., Abdoli, M. A., Bozorg Haddad, O., & Pazoki, M. (2022). The Impact of Hydrothermal Carbonization Treatment on Anaerobic Digestion of Organic Fraction of Municipal Solid Waste. *Environmental Energy and Economic Research*, *6*(1), 1–10.

Guo, S., Mu, J., Gao, L., Ge, L., & Lisak, G. (2024). Enhancing energy yield and reducing environmental impact through co-hydrothermal carbonization of undehydrated sewage sludge and fungus bran. *Journal of Environmental Chemical Engineering*, *12*(5), 114051.

Hämäläinen, A., Kokko, M., Kinnunen, V., Hilli, T., & Rintala, J. (2021). Hydrothermal carbonisation of mechanically dewatered digested sewage sludge—Energy and nutrient recovery in centralised biogas plant. *Water Research*, *201*, 117284.

Heidary, R. (2017). Effect of temperature on hydrothermal gasification of paper mill waste, case study: the paper mill in North of Iran. *Journal of Environmental Studies*, *43*(1), 59–71.

Kang, K., Nanda, S., Sun, G., Qiu, L., Gu, Y., Zhang, T., Zhu, M., & Sun, R. (2019). Microwave-assisted hydrothermal carbonization of corn stalk for solid biofuel production: Optimization of process parameters and characterization of hydrochar. *Energy*, *186*, 115795.

Kannan, S., Gariepy, Y., & Raghavan, G. S. V. (2017). Optimization and characterization of hydrochar produced from microwave hydrothermal carbonization of fish waste. *Waste Management*, *65*, 159–168.

Kruse, A., Funke, A., & Titirici, M.-M. (2013). Hydrothermal conversion of biomass to fuels and energetic materials. *Current Opinion in Chemical Biology*, *17*(3), 515–521.

Liu, Z., & Balasubramanian, R. (2012). Hydrothermal carbonization of waste biomass for energy generation. *Procedia Environmental Sciences*, *16*, 159–166.

Lu, X., Ma, X., & Chen, X. (2021). Co-hydrothermal carbonization of sewage sludge and lignocellulosic biomass: fuel properties and heavy metal transformation behaviour of hydrochars. *Energy*, *221*, 119896.

Lynam, J. G., Coronella, C. J., Yan, W., Reza, M. T., & Vasquez, V. R. (2011). Acetic acid and lithium chloride effects on hydrothermal carbonization of lignocellulosic biomass. *Bioresource Technology*, *102*(10), 6192–6199.

Maleki Delarestaghi, R., Ghasemzadeh, R., Mirani, M., & Yaghoubzadeh, P. (2018). The comparison between different waste management methods of Tabas city with life cycle assessment assessment. *Journal of Environmental Science Studies*, *3*(3), 782–793. Retrieved from https://www.jess.ir/article_81252.html

Nizamuddin, S., Jaya Kumar, N. S., Sahu, J. N., Ganesan, P., Mubarak, N. M., & Mazari, S. A. (2015). Synthesis and characterization of hydrochars produced by hydrothermal carbonization of oil palm shell. *The Canadian Journal of Chemical Engineering*, *93*(11), 1916–1921.

Nizamuddin, S., Mubarak, N. M., Tiripathi, M., Jayakumar, N. S., Sahu, J. N., & Ganesan, P. (2016). Chemical, dielectric and structural characterization of optimized hydrochar produced from hydrothermal carbonization of palm shell. *Fuel*, *163*, 88–97.

Parshetti, G. K., Liu, Z., Jain, A., Srinivasan, M. P., & Balasubramanian, R. (2013). Hydrothermal carbonization of sewage sludge for energy production with coal. *Fuel*, *111*, 201–210.

Pauline, A. L., & Joseph, K. (2020). Hydrothermal carbonization of organic wastes to carbonaceous solid fuel–A review of mechanisms and process parameters. *Fuel*, *279*, 118472.

Pazoki, M., Ghasemzadeh, R., Pazoki, M., & Ghasemzadeh, R. (2020). Leachate quality. *Municipal Landfill Leachate Management*, 101–127.

Pazoki, M., Ghasemzadeh, R., Yavari, M., & Abdoli, M. A. (2018). Analysis of photocatalyst degradation of erythromycin with titanium dioxide nanoparticle modified by silver. *Nashrieh Shimi va Mohandesi Shimi Iran*, *37*(1), 63–72.

Reza, M. T., Andert, J., Wirth, B., Busch, D., Pielert, J., Lynam, J. G., & Mumme, J. (2014). Hydrothermal carbonization of biomass for energy and crop production. *Appl. Bioenergy*, *1*(1), 11–29.

Reza, M. T., Lynam, J. G., Uddin, M. H., & Coronella, C. J. (2013). Hydrothermal carbonization: Fate of inorganics. *Biomass and Bioenergy*, *49*, 86–94.

Sabio, E., Álvarez-Murillo, A., Román, S., & Ledesma, B. (2016). Conversion of tomato-peel waste into solid fuel by hydrothermal carbonization: Influence of the processing variables. *Waste Management*, *47*, 122–132.

Tag, A. T., Duman, G., & Yanik, J. (2018). Influences of feedstock type and process variables on hydrochar properties. *Bioresource Technology*, *250*, 337–344.

Tajfar, I., Pazoki, M., Pazoki, A., Nejatian, N., & Amiri, M. (2023). Analysis of Heating Value of Hydro-Char Produced by Hydrothermal Carbonization of Cigarette Butts. *Pollution*, *9*(3), 1273–1280.

Wang, R., Lin, K., Peng, P., Lin, Z., Zhao, Z., Yin, Q., & Ge, L. (2022). Energy yield optimization of co-hydrothermal carbonization of sewage sludge and pinewood sawdust coupled with anaerobic digestion of the wastewater byproduct. *Fuel*, *326*, 125025.

Yan, M., Chen, F., Li, T., Zhong, L., Feng, H., Xu, Z., Hantoko, D., & Wibowo, H. (2023). Hydrothermal carbonization of food waste digestate solids: Effect of temperature and time on products characteristic and environmental evaluation. *Process Safety and Environmental Protection*, *178*, 296–308.

Zhang, X., Gao, B., Zhao, S., Wu, P., Han, L., & Liu, X. (2020). Optimization of a "coal-like" pelletization technique based on the sustainable biomass fuel of hydrothermal carbonization of wheat straw. *Journal of Cleaner Production*, *242*, 118426.

Zheng, X., Shen, M., Ying, Z., Feng, Y., Wang, B., & Dou, B. (2022). Correlating phosphorus transformation with process water during hydrothermal carbonization of sewage sludge via experimental study and mathematical modelling. *Science of the Total Environment*, *807*, 150750.