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Hydrogen rich syngas production through sewage sludge pyrolysis: A comprehensive experimental investigation and performance optimisation using statistical analysis

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A R T I C L E I N F O

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A B S T R A C T

Bioenergy is anticipated to play a significant role in the United Kingdom's Net Zero 2050 scenario. This study aims to explore the possibility of producing hydrogen-rich syngas using sewage sludge from a wastewater treatment plant located in England, United Kingdom. The primary objective of this study is to experimentally produce hydrogen-rich syngas from sewage sludge through pre-treatment, drying, and pyrolysis. Furthermore, statistical methods have been employed to optimise the performance of the pyrolyser. The individual desirability scores for lower heating value (LHV) and cold gas efficiency (CGE) were estimated to be 0.83902 and 0.85307, respectively. Combining these scores, the overall desirability of the model reached 0.8460, indicating favourable predictive performance. The optimal operational conditions are reported to be a feed rate of 3.0488 revolutions per minute (rpm) and an operational temperature of 800°C. Under these conditions, the highest calculated CGE of 66.31% and the peak LHV value of 18.36 MJ/ mˆ3 were achieved.

1. Introduction

1.1. Background and motivation of the study

As of 2021, bioenergy accounted for 12.9% of the total electricity supply in the United Kingdom, making it the second-largest renewable energy source. This expansion is anticipated to continue in the decades to come (Booth and Wentworth, 2023). According to Wang et al. (2020), there has been a significant increase in the production of sewage sludge due to ongoing developments population growth, and rising pollution from industrialization. Sewage sludge, a semi-solid substance classified as biomass, materialises through physicochemical processes linked with wastewater treatment. As a result, the appropriate handling of wastewater has become a vital global obligation, in line with the objectives specified by the United Nations Sustainable Development Goals (SDGs) (Migliaccio et al., 2021). Most sewage sludge is converted to fertiliser by chemical stabilisation (alkaline lime stabilisation) or biological stabilisation (anaerobic digestion) (Mulchandani and Westerhoff, 2016). This sludge comprises a significant amount of organic and inorganic microplastics such as pathogens, bacteria, viruses, heavy metals, and other chemicals(Fijalkowski et al., 2017). Additionally, the environment and human health are adversely affected by microplastics and pathogens that enter agricultural landfills via sludge.

In this scenario, pyrolysis or gasification technologies play a critical role in both reducing the amount of waste produced and generating hydrogen-rich syngas from sludge (Kobayashi and Kuramochi, 2023). Pyrolysis involves thermally breaking down sludge at temperatures above 300°C without the use of an oxidising agent (Djandja et al., 2020; Dong et al., 2020). The sludge's molecular structures start to disintegrate during this process into three phases: pyrolysis oil, gaseous components, and char, a solid mass that contains carbon (Dong et al., 2020). Pyrolysis reduces methane emissions from anaerobic decomposition in landfills by turning organic matter in sewage sludge into biochar. Because of high absorbability, rich porous structure, and presence of multiple functional groups, the biochar that is produced from sewage sludge is suitable for a range of applications. This includes air pollution control, wastewater treatment, soil reduction, serving as a fertiliser (Ramrakhiani et al., 2022), controlling air pollution, carbon capture and storage, and other industrial uses (Khan et al., 2023). There are fewer contaminants and particulates released in pyrolysis if advanced

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filtration technology is employed. Furthermore, the quantity of dioxin formation reduces in the absence of oxygen.

1.2. Literature review

Numerous prior studies have examined the production of H_2-rich syngas through the pyrolysis of biomass wastes. For example, Wen et al. (2022) conducted a simulation study on the pyrolysis of agricultural waste coupled with the hydrothermal carbonization process. They reported that the molar ratio of H_2 to CO reached its peak value of 9.2 when a pyrolysis temperature of 450°C was employed using solely the hydrothermal carbonization process. In a separate study, Zhang et al. (2023) investigated the microwave-assisted gasification of corn stover and reported a higher syngas yield than that obtained from a microwave-assisted pyrolysis process, even at a high temperature of 900°C. In another study, Li et al. (2023) conducted experimental research on cornstalk pyrolysis using a two-stage electromagnetic induction reactor. They reported the following pyrolysis product distribution: 69.6 wt% gas, 15.6 wt% char, 7.8 wt% coke, 2.2 wt% oil, and 4.8 wt% H_2O. The gas composition primarily consisted of 45.7% H_2 and 43.8% CO by volume, respectively. In a separate study, Beik et al. (2023) a prototype twin auger pyrolysis reactor for the treatment of sanitary sludge was investigated. They reported a prototype reactor yield of 50% for biooil, 40% for syngas, and 10% for biochar at a temperature of 500°C. In a separate study, Xu et al. (2021) conducted an experimental study on the co-pyrolysis of rice husk and plastic wastes using a bench-scale fixed bed and a Ni/char catalyst. Their findings indicated that the highest positive synergy in terms of syngas quality was achieved when the polyethylene content was at 75%. Al-Rumaihi et al. (2023) investigated the pyrolysis of various feedstocks, including biomass and polymer wastes, and their combinations using Aspen Plus. They reported that the Pyrgas was a major product, with 623.78 kg/hr for camel manure and 555.69 kg/hr for date pits at higher temperatures. Temireyeva et al. (2024) investigated low and fast pyrolysis of flax straw biomass employing Aspen Plus and reported that in slow pyrolysis, energy efficiency ranged from 88.3% to 95.3% and exergy efficiency ranged from 86.9% to 94.8%, whereas in fast pyrolysis, exergy efficiency ranged from 88.9% to 98.0% and energy efficiency varied from 89.5% to 98.2%. K et al. (2023) modelled biomass pyrolysis using Simulink and Aspen Plus and compared the results. The simulations were performed at 700–1100 K and steam partial pressures of about 1 bar.

Some studies based on sewage sludge can be found in the literature. For example, Pan et al. (2023) explored co-pyrolysis of sewage sludge and rice husk for syngas production. They achieved a substantial 41.55% increase in the lower heating value (LHV) of pyrolysis syngas for energy recovery, raising it from 7.99 MJ/Nm^3 to 11.31 MJ/Nm^3 using synergistic optimisation techniques. In another numerical study, Zhou et al. (2023) studied municipal sewage sludge pyrolysis and carbonization using the Aspen Plus simulation platform. They advised an initial sludge moisture content of 60%, a pyrolysis temperature of approximately 400 °C, post-drying moisture content of around 30%, and recommended maintaining an incinerator's excess air coefficient between 2.6 and 2.8 whenever feasible.

Very few statistical optimisation-based pyrolysis studies can be found in the literature. For example, Tomasek et al. (2022) conducted a pyrolysis study on biomass-rich municipal solid waste using a nickel-supported ZSM-5 catalyst. They applied response surface modeling (RSM) to analyse the process. The study revealed that the optimal operating conditions for the two-step pyrolysis of biomass-rich municipal solid waste were a temperature of 850 °C and a steam rate of 1 g/h. Under these conditions, they observed a gas yield of 27.1%, a hydrogen yield of 9.96 mmol g^{-1} waste, and a hydrogen/carbon monoxide molar ratio of 1.8. In another study, Prajapati et al. (2022) experimentally studied pyrolysis products of diverse biomass waste: pigeon pea, sun hemp, mustard stem, wheat straw, Sesbania bispinosa, and Ocimum gratissimum. They applied statistical analysis, including ANOVA, and found that non-condensable biogases from different biomass samples typically contained 40–55 vol% hydrogen, 8–25 vol% methane, 1–12 vol% carbon monoxide, and 12–50 vol% carbon dioxide. In another study, Zaman and Ghosh (2021) investigated steam gasification of biomass in Aspen Plus software, and further employed statistical analysis to optimise the performance of the gasification process. Their findings indicated that the optimal performance was achieved at gasification temperatures within the range of 780–790°C, resulting in a 70% cold gas efficiency.

1.3. Novelty and contribution of the study

It can be inferred from the previous literature review section that, although there have been some studies on the pyrolysis of sewage sludge, most of these studies have been limited to parametric analysis. Very few optimisation studies, as well as experimental investigations, can be found in the literature. Considering these facts, and with the aim of addressing this research gap, this study attempts to experimentally investigate the potential of generating hydrogen-rich syngas through the utilisation of sewage sludge sourced from a wastewater treatment plant in England, United Kingdom. The schematic representation of the overview of the study is depicted in Fig. 1. The primary objective was to investigate the viability of this process through practical experimentation. To begin with, the sewage sludge underwent a series of pretreatment steps, followed by a drying process aimed at maintaining an optimal moisture level conducive to the subsequent thermochemical reactions. A comprehensive analysis was then undertaken to assess the quality of the resulting hydrogen-rich syngas. Moreover, statistical methodologies were employed to optimise the performance. This study aims to provide valuable understanding regarding hydrogen-rich syngas production from sewage sludge, employing experimental techniques and statistical methods.

The major contributions of the study are listed below:

- An experimental investigation of sewage sludge pyrolysis has been performed to generate hydrogen-rich syngas.
- In-depth analysis of pyrolysis products has been done using experimental techniques.
- Sensitivity analysis has been performed to investigate the performance of major design parameters, such as feed rate and temperature on the pyrolysis process.
- Statistical analysis has been employed to perform multi-objective optimisation of the pyrolysis process in order to maximise the cold gas efficiency and the lower heating value of the hydrogen-rich syngas.

2. Materials and methods

2.1. Characterisation of tested material and its pretreatment

Continuous research is being carried out on techniques to use sewage sludge as a biomass resource and convert it into fuel (Zhou et al., 2023). The moisture content of sewage sludge from the treatment facilities varies from 40% to 85% depending upon the adopted methods(Adibimanesh et al., 2023; Zhang et al., 2022). However, prior to pyrolysis, the sludge needs to be dried. Sludge drying should be considered not only as a necessary but also as an integrated process when considering a variety of sludge thermal utilisation methods. Sludge is substantially more thoroughly dewatered by thermal drying than by the most advanced dewatering techniques. As shown in Fig. 1, the wet sludge has been dried with the use of tumbler drier up to 15% moisture content.

The properties of sludge sample are tabulated in Table 1.

The fixed carbon (FC) is estimated by the following relation (Petrovič et al., 2023).

$$FC \quad (\%) = 100 - VM - Ash \tag{1}$$

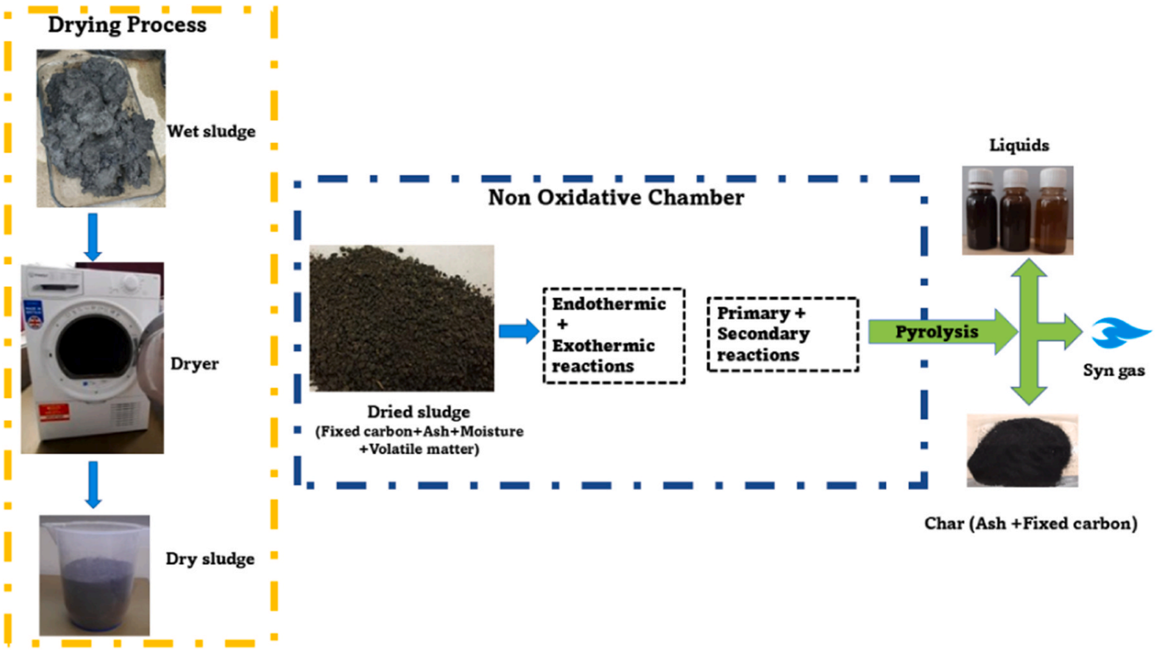

Fig. 1. Overview of the study.

Table 1
Properties of sludge.

Properties			
	Moisture content	wt%	15
Proximate analysis			
	Ash content	wt%	36.3
	Volatile matter	wt%	56.6
	Fixed carbon	wt%	7.1
Ultimate analysis			
	Carbon	wt%	30.9
	Hydrogen	wt%	4.6
	Oxygen	wt%	58.7
	Nitrogen	wt%	4.5
	Sulphur	wt%	1.3

where VM is the volatile matter.

The oxygen content is estimated by the equation provided below (Petrovič et al., 2023).

$$O(wt\%) = 100 - C - H - N - S - Ash \quad (all \quad in \quad wt\%) \tag{2}$$

2.2. Fourier transform infrared (FTIR) analysis

Fourier transform infrared (FTIR) spectra of the samples were recorded by a PerkinElmer FTIR spectrophotometer equipped with a Perkin–Elmer FTIR software for accurate and high reproducibility of spectral data. The chemical composition of sewage sludge has significantly changed following thermal treatment, as shown by comparing the FTIR spectra of the raw and dried sludge spectra.

Fig. 2 illustrates the FTIR spectra of both raw sludge and dried sludge samples. Notably, the raw sludge sample exhibits a prominent broad peak within the 3700 cm^{-1} range, which corresponds to the vibrations of O-H groups, primarily associated with alcohol compounds. Vibrations stemming from the N–H groups of both primary and secondary amines are also observable in the 3500–3300 cm^{-1} range. Peaks found at 2550 cm^{-1} and 1930 cm^{-1} align with the vibrations of aliphatic S-H bonds and C-H bonds, likely indicating the presence of thiol and aromatic compound classes. In the spectrum, the intervals between 1370 and 1335 cm^{-1} capture the vibrations arising from the S═O group within sulfonate and sulfonamide compound classes. Additionally, a distinctive peak located at 886 cm^{-1} corresponds to C═C vibrations characteristic of the alkene compound class. The dried sludge's spectrum displays variations from that of the raw sludge. Specifically, the intensity of certain peaks, like the one corresponding to the O-H groups, diminishes as a result of the dehydration reaction that takes place during the drying process. For the samples treated by the drying process, the variations are even more evident, as the peaks for the aliphatic S═H bonds, thiol groups and aromatic groups are lower, indicating that a desulfonation reaction happened during the process. In comparison to raw sludge, the dried sludge has less vibrations of the N–H groups of the primary and secondary amines in 3500 cm^{-1} to 3300 cm^{-1} range.

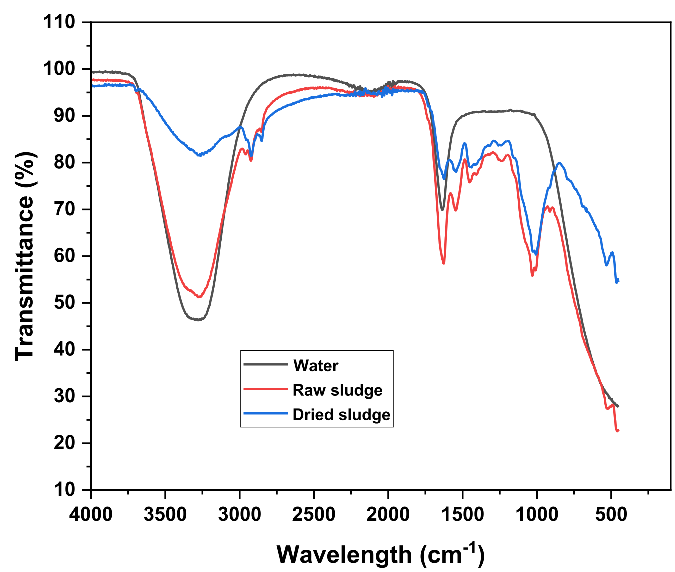

Fig. 2. FTIR spectra of Raw sludge and dried sludge samples.

2.3. Experimental setup and description

Fig. 3 illustrates the experimental setup of Hybrid Gasification Limited (HGL) make pyrolysis system, which comprises various

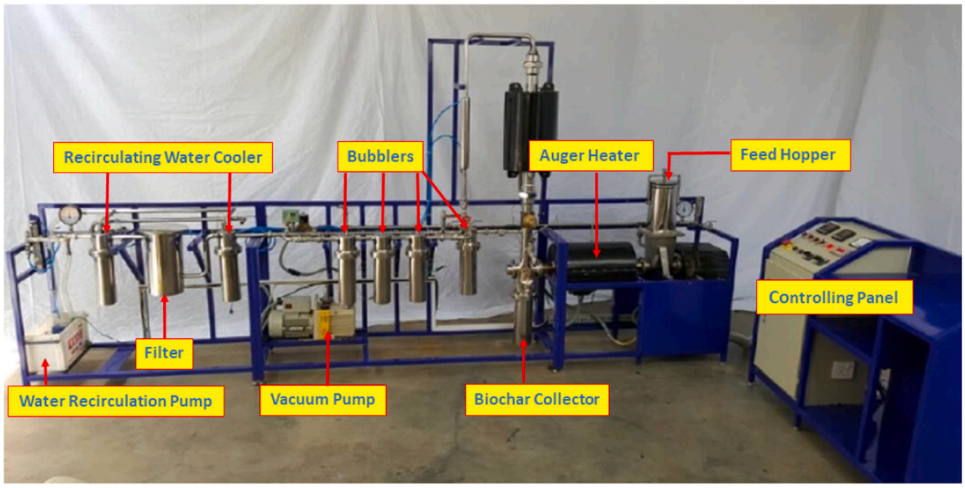

Fig. 3. Experimental setup of pyrolysis system.

components including the biochar-collector, auger-heater, vacuum-pump, water-recirculation-pump, filter, recirculating-water-cooler, bubblers, eed-hopper, and controlling-unit. The feed material utilised in this system is sludge, which is introduced into the gasifier through a sealed chamber. Prior to adding the feed material, the heating chamber of the gasifier is heated to desired operating temperatures ranging up to 900°C. This elevated temperature facilitates the conversion of the solid material into syngas, residual organic oils/tars, and ash. Operating at pressures below 0.3 bar above atmospheric pressure, the system's pressure is carefully regulated by an automatic safety valve. This valve ensures safe venting of excess pressure to the outside atmosphere through an extraction fan venting system. The resulting hot ash is collected within a sealed stainless steel ash collector, where it will remain until it cools for subsequent analysis. The generated gases, including syngas and residual oils/tars, are directed through a sequence of three water bubble chambers. These chambers serve to cool the gases and extract any remaining residual oils/tars. The water containing these residual components is collected in appropriate containers for further analysis. The remaining syngas is then guided through two cooling coils and a filter before reaching the outlet valve. At this valve, the gas can be collected for future analysis using suitable gas sampling bags. Any excess gas is incinerated by a Bunsen burner. Following the completion of tests, the gasifier heater is deactivated, and the system is allowed to cool down to a safe temperature (below 150°C). This cooling process ensures that the auger can be turned off without risking damage and can safely cool overnight.

2.4. Gas characterisation

The pyrolysis gas produced by the sample was analysed by Cubic-Ruiyi-Gasboard-3100 is a stationary syngas analyser based on NDIR, TCD and electrochemical technology. This analyser measures main gases (CO, CO_2 CH_4, N_2, H_2, C_2H_4 and C_nH_m) simultaneously and is given as a percentage of total gas through the analyser. Also, net calorific value of gas in terms of low heat value can be measured by this gas analyser. The cold gas efficiency (CGE) has been estimated by the following equation.

$$CGE = \frac{m_{syn} \times LHV_{syn}}{(m_{biomass} \times LHV_{biomass}) + Q} \quad (3)$$

where m_{syn} and $m_{biomass}$ are mass flowrate of syngas and biomass, respectively. LHV_{syn} and $LHV_{biomass}$ are the lower heating values of syngas and biomass, while Q refers to the amount of heat supplied to the reactor.

3. Results and discussion

3.1. Syngas analysis

In this subsection, parametric analysis on the syngas compositions has been performed under varying conditions. The hydrogen yield mainly depends on high pyrolysis temperature, feedstock feed rates through the system relative to the auger speed, and particle size of feedstock with longer residence durations and heating rates. Fig. 4 depicts the syngas compositions observed during a series of experiments conducted under these varying conditions, which are provided in Table 2. The operating temperature ranges have been selected as 800–900°C (Lumley et al., 2014).

Analysing the obtained results, it is clear that the highest hydrogen yield is observed in state E, where the feed speed is 5 rpm and the temperature is 850 °C followed by conditions H and I, respectively exhibit high hydrogen production in descending order. These data clearly indicate that hydrogen production depends on feed rate and temperature, with the optimal combination being in the E-condition.

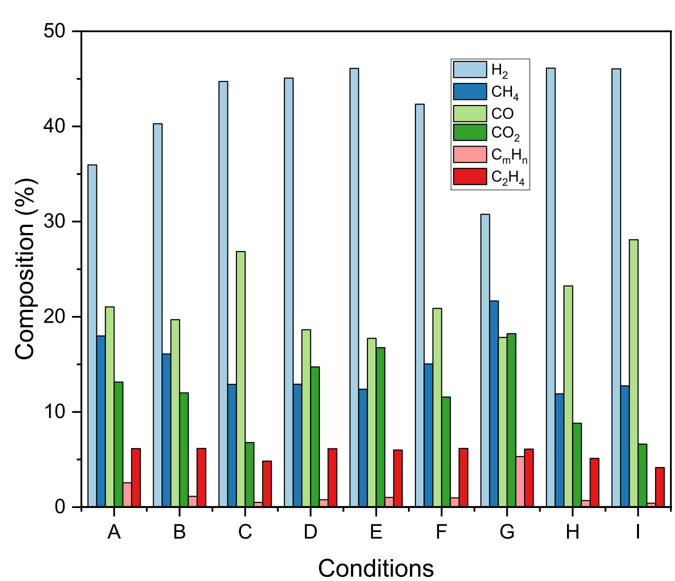

Fig. 4. Syngas compositions observed during experiments under different conditions.

Table 2
Operating conditions.

State	A	B	C	D	E	F	G	H	I
Feed rate (rpm)	3	3	3	5	5	5	10	10	10
Temperature (°C)	800	850	900	800	850	900	800	850	900

3.2. Statistical analysis

This work involved a series of investigations in a novel pyrolysis unit to produce syngas from sewage sludge under various operating temperatures and auger feed rate conditions. The primary focus was to assess the impact of these different parameter combinations on the composition and quality of the resulting syngas. The main objective was to identify the optimal operating parameters that would produce the utmost cold gas efficiency while also maximising the benefits of the lower heating value. Using the Minitab program, a thorough statistical analysis was carried out to perform the aforementioned objective. A thorough analysis of the process-influencing components was obtained using Analysis of Variance (ANOVA). ANOVA made it easier to develop reliable regression models, which offered a predictive framework for process optimisation and also, helped to explain the correlations between the various factors.

Table 3 displays the outcomes obtained from the ANOVA analysis conducted on the CGE model. The F value (30.06) is observed to hold significance. It is important to emphasise that there exists a mere 0.01% probability for an F-value of such magnitude to arise due to random fluctuations. Furthermore, the p-values that fall below the threshold of 0.05 serve as indicators that the model terms bear substantial significance. Within the context of the regression model, it is noted that the p-value for the model itself is 0.001, underlining its statistical significance. Moreover, both design variables, namely feed rate and operating temperature, are found to carry significance within the scope of the analysis.

The simple regression model has been applied for the CGE and it has been shown below:

$$\ln(CGE) = 5.397 - 0.0095 \times Feed \quad rate - 0.001467 \times Temperature \tag{4}$$

The R^2 and R^2_{adj} values of CGE are found to be higher which are 90.93% and 87.97%, respectively. Thus, the CGE regression model exhibits a greater degree of accuracy.

Displayed in Fig. 5 is the Pareto chart illustrating the significance of the variables, Feed rate, and Temperature, with respect to the CGE model. Notably, both variable bars intersect the reference line at 1.65, indicating a substantial influence of both factors on the response variable, cold gas efficiency.

Table 4 presents the results derived from the ANOVA analysis applied to the LHV model. The F value (32.05) demonstrates notable significance, highlighted by an exceedingly low probability of 0.01% for such a substantial F-value to arise due to random variability. Furthermore, the p-values falling below the threshold of 0.05 signal the noteworthy significance of the model terms. Notably, the p-value for the model itself is 0.001, underscoring its statistical importance within the regression model. Additionally, both design variables, Feed rate and operating temperature, hold significance within the context of the analysis.

The simple regression model has been employed for LHV, as presented below:

$$\ln(LHV) = 3.998 - 0.00956 \times Feed \quad rate - 0.001323 \times Temperature \tag{5}$$

The LHV regression model demonstrates a higher degree of accuracy, with R^2 and R^2_{adj} values of 91.44% and 88.59%, respectively.

In Fig. 6, the Pareto chart illustrates the significance of the variables, Feed rate, and Temperature, on the LHV model. Notably, both variable bars intersect the reference line at 1.65, indicating that both factors significantly impact the response variable, LHV.

3.3. Sensitivity analysis

The changes in cold gas efficiency (CGE) concerning the feed rate are depicted in Fig. 7**(a).** Notably, it is evident that the CGE value decreases as the feed rate increases. It is due the fact that the reaction time available for the pyrolysis reduces as the feed rate increases resulting lower syngas yield which in turn lowers CGE. Referring to Fig. 7**(b),** it is evident that an increase in the operating temperature from 800°C to 900°C corresponds to lower values of CGE. Fig. 8**(a)** illustrates the variations in LHV as the feed rate is increased within the range of 3–10 rpm. The curve follows the same trend as observed in **Figure7(a).** Notably, a consistent decrease in LHV values is observed as the feed rate increases. It is also due the fact that the reaction time available for the pyrolysis reduces as the feed rate increases resulting lower hydrogen yield which reduces LHV. As indicated in Fig. 8**(b),** elevating the operating temperature within the range of 800–900°C leads to a decrease in the values of syngas LHV.

3.4. Interaction effect of decision parameters on objective responses

The interaction between operating temperature and feed rate on CGE is depicted in Fig. 9. The optimal CGE values, surpassing 65%, manifest within the feed rate range of 3–5.1 rpm, coupled with operating temperatures spanning 800–814°C. Conversely, the least favourable CGE values, dipping below 55%, materialise when feed rates range from 7 to 10 rpm, alongside operating temperatures spanning 820–900°C. Similarly, the interaction between operating temperature and feed rate on syngas LHV is presented in Fig. 10. The peak syngas LHV value, exceeding 18 MJ/mˆ3, is achieved with feed rates ranging from 3 to 5.1 rpm, and operating temperatures between 800 and 814°C. Conversely, lower LHV values, below 55%, are noted at feed rates of 7–10 rpm, accompanied by operating temperatures spanning 820–900°C. It is noteworthy that the interaction of operating temperature and feed rates demonstrates consistent trends for both objectives, namely, CGE and LHV.

Table 3
ANOVA for cold gas efficiency (CGE).

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	2	0.039375	90.92%	0.039375	0.019688	30.06	0.001
Feed rate (rpm)	1	0.007090	16.37%	0.007090	0.007090	10.82	0.017
Temperature (°C)	1	0.032286	74.55%	0.032286	0.032286	49.29	<0.001
Error	6	0.003930	9.08%	0.003930	0.000655		
Total	8	0.043305	100.00%				

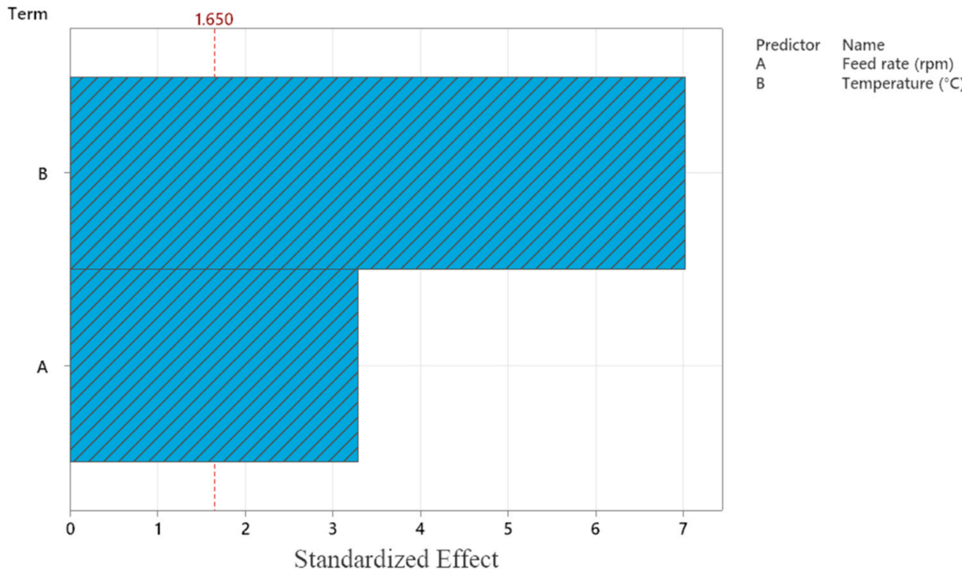

Fig. 5. Pareto chart for variable influence on CGE.

Table 4
ANOVA for lower heating value (LHV).

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.033403	91.44%	0.033403	0.016701	32.05	0.001
Feed rate (rpm)	1	0.007134	19.53%	0.007134	0.007134	13.69	0.010
Temperature (°C)	1	0.026269	71.91%	0.026269	0.026269	50.41	<0.001
Error	6	0.003126	8.56%	0.003126	0.000521		
Total	8	0.036529	100.00%				

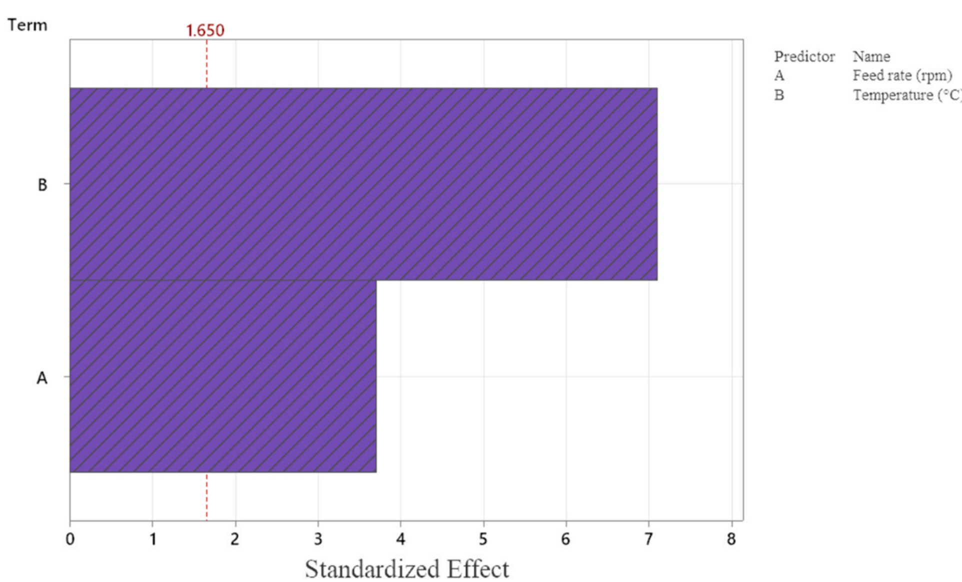

Fig. 6. Pareto chart for variable influence on LHV.

3.5. *Multi-objective Optimisation*

In this sub-section, multi-objective optimisation has been performed using the "Response Optimiser" tool embedded in the Minitab software. The optimisation constraints and the objectives of the study are provided in Table 5.

Each response undergoes a conversion into a dimensionless desirability value denoted as ’d’ using desirability analysis. This value which ranges from 0 to 1, serves as an indicator for the level of desirability achieved. A value of 1 implies outcomes that are highly desirable, while a value of 0 means results deemed that are unacceptable. The cumulative desirability, indicated as ’D’, is mathematically expressed as follows (Ghodsiyeh et al., 2014):

$$D = [d_1(y_1) \times d_2(y_2) \times d_3(y_3) \times \ldots\ldots\ldots\ldots d_n(y_n)]^{1/n} \quad (6)$$

where, n is the number of responses.

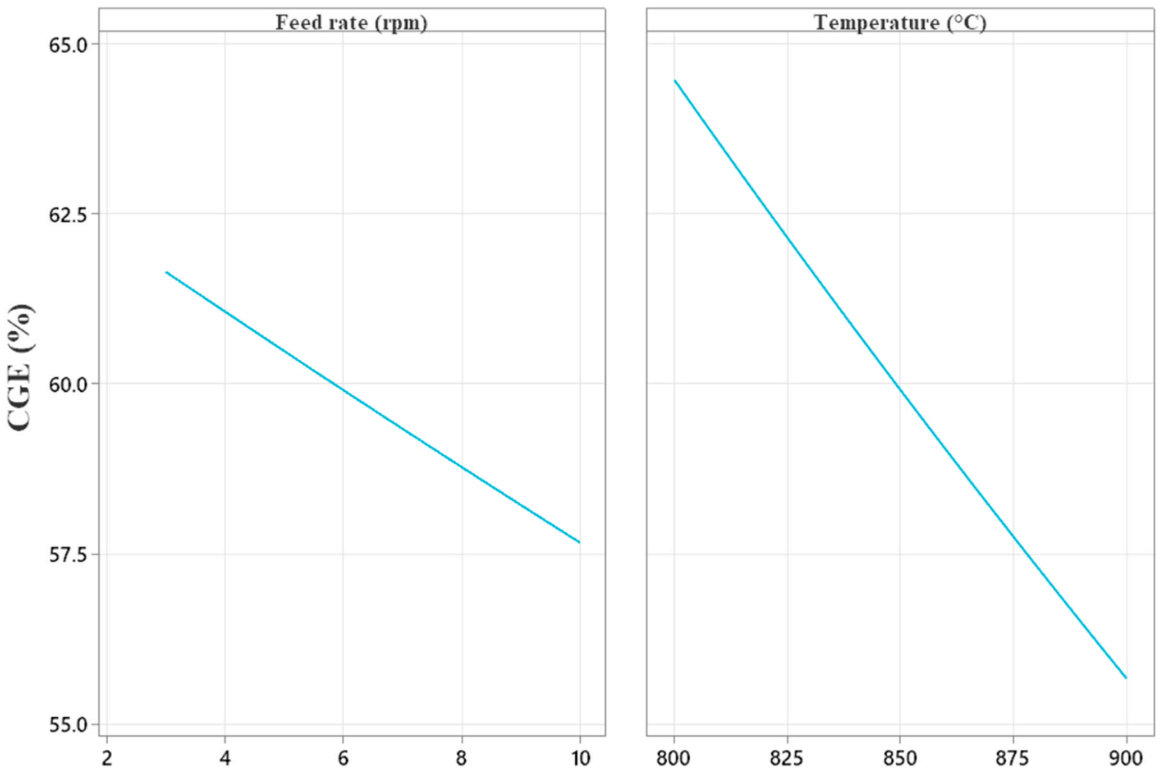

Fig. 7. Effect of (a)feed rate and (b) temperature on CGE.

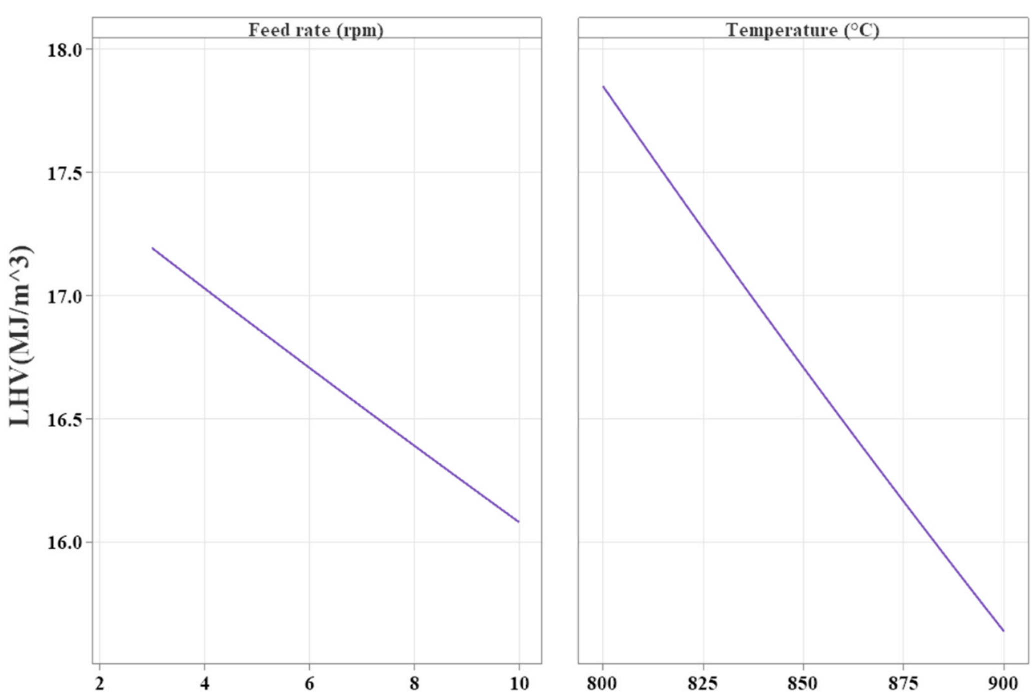

Fig. 8. Effect of (a)feed rate and (b) temperature on LHV.

The individual desirability values for LHV and CGE design variables were determined to be 0.83902 and 0.85307, respectively. Combining these values, the overall desirability of the model attained 0.8460, indicating favourable predictive performance. Fig. 11 depicts that statistical analysis identified the optimal operating conditions of a feed rate of 3.0488 rpm and an operational temperature of 800°C. Under optimal operating conditions, the highest CGE of 66.31% and the peak LHV value of 18.36 MJ/mˆ3 were attained.

4. Conclusions

Due to increasing urbanisation and continuing social improvements, global wastewater production has increased significantly. This trend highlights the urgent need to improve the existing sewage treatment

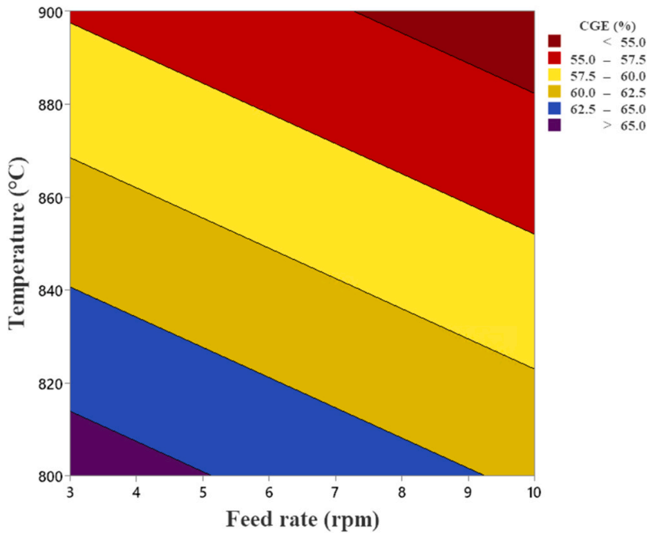

Fig. 9. Interaction consequence of Temperature and Feed rate on CGE.

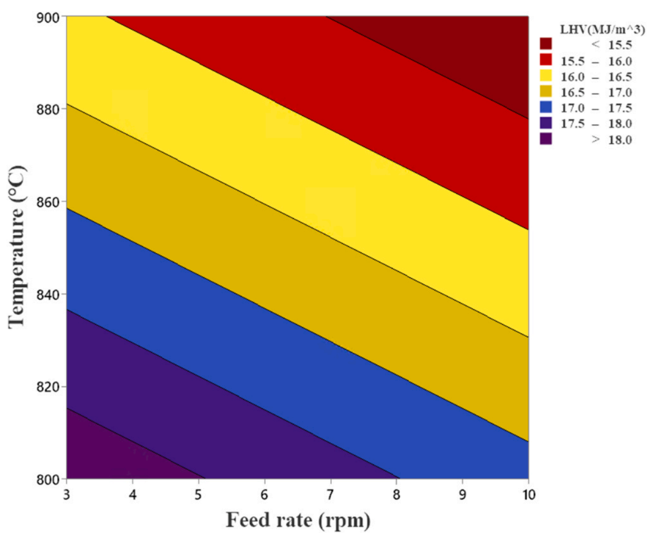

Fig. 10. Interaction consequence of Temperature and Feed rate on syngas LHV.

Table 5
Optimisation constraints and objectives.

Parameters	Range/objective
Feed rate (rpm)	3–10
Operating temperature (°C)	800–900
Cold gas efficiency (%)	Maximise
Lower heating value (MJ/mˆ3)	Maximise

systems. In this context, sewage sludge handling has emerged as an important challenge, requiring the attention of government agencies and utilities worldwide. In this study, an attempt has been made to experimentally investigate the potential of generating hydrogen-rich syngas through the utilisation of sewage sludge obtained from a wastewater treatment plant located in England, United Kingdom. The main objective of the study was to investigate feasibility assessment of this process through practical experimentation. A series of pre-treatment steps were conducted to treat the wastewater, followed by sludge drying. Furthermore, dried sludge undergone through pyrolysis to generate hydrogen-rich syngas. Moreover, statistical methods were employed to optimise the performances. The major results are listed below.

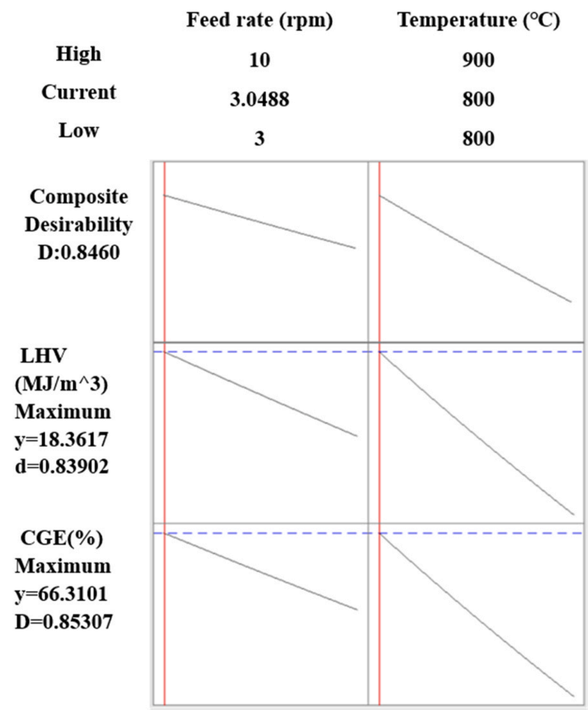

Fig. 11. Response optimiser plot.

- The LHV regression model establishes a higher degree of accuracy, with R^2 and R^2_{adj}values of 91.44% and 88.59%, respectively.
- The R^2 and R^2_{adj} values of CGE are found to be higher which are 90.93% and 87.97%, respectively.

- The individual desirability scores for LHV and CGE design variables were estimated to be 0.83902 and 0.85307, respectively. Combining these scores, the overall desirability of the model reached 0.8460, representing a favourable predictive performance.
- Statistical analysis identified the optimal operating conditions of a feed rate of 3.0488 rpm and an operational temperature of 800°C. Under the optimal operating conditions, the highest CGE of 66.31% and the peak LHV value of 18.36 MJ/mˆ3 were attained.

However, it will be interesting to improve the design of the experimental setup by incorporating some changes such as exploring novel catalysts and process improvements to have a better conversion of biomass and tar cracking to produce a higher amount of hydrogen. Also, exploration of alternative feedstocks will be conducted in future. Nevertheless, the present study adds to the ongoing discourse about the sewage treatment challenges amidst urbanisations. By exploring innovative approaches such as generating hydrogen-rich syngas from sewage sludge, waste disposal could be improved in the United Kingdom.

CRediT authorship contribution statement

Kumar Vijayalakshmi Shivaprasad: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jonathan Heslop:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Dibyendu Roy:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Abdullah Malik:** Conceptualization, Funding acquisition, Methodology, Resources, Writing – review & editing, Formal analysis, Visualization. **Yaodong Wang:** Funding acquisition, Project administration, Visualization, Writing – review & editing, Resources, Supervision. **Anthony Paul Roskilly:** Funding acquisition, Resources, Software, Supervision, Writing – review & editing. **Huashan Bao:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

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.

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