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Interaction effect and optimisation of temperature and residence time of co-pyrolysis for liquid fuel production

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Abstract

Increasing the added value of multi-component municipal solid waste (MSW) through thermochemical conversion provides dual benefits: reducing urban waste accumulation and generating renewable energy. In rapidly growing urban areas with increasing waste volumes, the urgency of converting waste into fuel is necessary. This study optimises pyrolysis process parameters to improve the yield and quality of liquid fuel derived from MSW. Using response surface methodology (RSM) and desirability function technique (DFT) allows optimal parameter prediction and minimises experimental costs. Experiments were conducted using a two-stage fixed-bed pyrolysis reactor with natural dolomite as a catalyst. Central composite design (CCD) was applied to ensure statistical reliability. The results show a nonlinear effect of temperature on the liquid and provide a maximum yield of 30.8 wt. %, while time plays a greater role in increasing the energy density to 9978 kcal/kg. The model showed a high coefficient of determination (R^2 = 0.9571) with optimal parameters identified at a temperature of 488.3 °C and a time of 202.1 minutes, and produced a liquid fuel with physicochemical characteristics comparable to commercial diesel. This study introduces a strategic pathway to accelerate the valorisation of MSW into high-quality fuels, which strengthens sustainable MSW management initiatives.

1. Introduction

The rapid increase in multi-component municipal solid waste (MSW) has become a pressing global concern, predominantly driven by accelerated urbanisation, population growth and evolving consumption patterns. Conventional waste management practices such as landfilling and incineration are proving insufficient to cope with this surge. These methods not only face capacity limitations but also aggravate environmental impacts through the emission of greenhouse gases, the generation of hazardous leachate and the depletion of land resources. The escalating urgency for sustainable waste-to-energy strategies has thus encouraged the exploration of technologies capable of reducing environmental burdens while recovering valuable energy and materials from waste streams. Within the range of thermochemical conversion processes, pyrolysis stands out as a promising pathway for converting organic-rich waste into liquid fuels, syngas and biochar under oxygen-limited conditions. Liquid fuels derived from pyrolysis offer renewable energy alternatives to fossil-derived fuels, while biochar can be used as a soil amendment and long-term carbon storage medium [1]. Nevertheless, the yield distribution and properties of these products are highly dependent on operational parameters such as feedstock composition, reactor temperature, heating rate and residence time.

Co-pyrolysis, in which two or more feedstocks undergo thermal conversion simultaneously, has gained recognition for its ability to improve both the yield and quality of pyrolytic products. This enhancement often arises from the complementary chemical characteristics of the feedstocks, such as hydrogen to carbon ratios and volatile content, which influence thermal degradation pathways and product selectivity. For instance, co-processing hydrogen-rich plastics with oxygenated biomass can optimise the hydrogen/carbon ratio, improving the calorific value and stability of the liquid fraction. Moreover, chemical interactions between different feedstock components may alter decomposition rates, reinforcing the importance of precise control over temperature and residence time [2]. While increased temperature promotes primary decomposition and light hydrocarbon generation, overheating can provoke secondary cracking reactions that reduce liquid yields in favour of gaseous products. Likewise, residence time strongly influences the balance between primary conversion and secondary reactions, thus affecting both the quantity and composition of the products [3]. Given the complex interplay of these parameters, optimising the temperature and residence time relationship is essential for achieving high yields and favourable quality in MSW co-pyrolysis.

Conventional trial-and-error approaches are often time-consuming, resource-intensive and less efficient, thus encouraging the adoption of advanced statistical optimisation techniques such as response surface methodology (RSM). RSM enables the construction of predictive empirical models that quantify the effects and interactions of process variables, allowing the identification of optimal conditions with reduced experimental effort [4]. Several studies have successfully applied RSM to pyrolysis systems. For instance, Sharma Timilsina et al. [5] employed RSM and compared the results with those obtained using artificial intelligence. Likewise, Kumar and Singh [6] performed the performance optimisation of process parameters by RSM for catalytic pyrolysis of high-density polyethylene waste to liquid fuel. Several other researchers have also reported the application of RSM for parameter optimisation in pyrolysis experiments [7].

Despite these advances, the interactive effects of temperature and residence time in MSW co-pyrolysis remain insufficiently explored, particularly with respect to simultaneous optimisation of yield and fuel quality. A deeper understanding of these interactions could enable the development of cost-effective, scalable waste-to-energy systems capable of accommodating the heterogeneous nature of MSW feedstocks. The present study addresses this gap by employing RSM as both an analytical and predictive tool to model and optimise the co-pyrolysis process. The objective is to define explicit relationships between key operating variables and liquid fuel performance, thereby providing a scientifically grounded framework for enhancing sustainable MSW management practices.

2. Materials, design and experimental

2.1 Materials

The feedstock used in this investigation consisted of a carefully prepared mixture of MSW fractions. The composition was fixed at 32 wt. % biomass residues, 54 wt. % post-consumer plastics, 9 wt. % recycled cardboard, 3 wt. % textile waste and 2 wt. % end-of-life tyre fragments, with each batch normalised to 500 g. Prior to thermal conversion, the materials underwent a rigorous pre-treatment process to ensure consistency and minimise variability in experimental outcomes. The preparation began with sieving to remove extraneous particulates and contaminants that might interfere with subsequent reactions. The sorted fractions were then sun-dried for three to five days, a step that reduced volatile content and minimised additional thermal energy requirements during processing. Once adequately dried, the materials were mechanically shredded and re-sieved to an average particle size of 3 to 5 cm, a dimension selected to maintain a steady feed rate and ensure homogeneity across all trials.

Natural dolomite, collected from a local mining source, was employed as the catalytic medium. Its elemental composition, determined via X-ray fluorescence analysis, revealed high concentrations of calcium oxide (CaO) of 56.13 wt. % and magnesium oxide (MgO) of 12.89 wt. %, along with minor amounts of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). The combination of CaO (a strong base) and MgO (a moderate base and structural stabiliser) provides bifunctionality, making it suitable for a variety of reactions requiring base activation. Minor additions of SiO_2 and Al_2O_3 sometimes give it a slight bifunctional acid-base property, although it retains its predominantly basic character. Further, for all experiments, the MSW to catalyst mass ratio was maintained at 500:500 g/g to standardise catalytic exposure. Before use, the dolomite was thermally activated by heating at 150 °C for three hours to discard residual volatiles and moisture, thereby enhancing catalytic activity. The activated dolomite was manually shaped into spherical pellets with diameters of 25 to 30 mm, facilitating uniform handling and consistent contact with the feedstock. Both MSW and catalyst pellets were stored in airtight containers to preserve their physical integrity and chemical stability until use.

2.2 Design of experiment

Process optimisation was carried out using RSM, with central composite design (CCD) as the experimental framework. Alternative statistical approaches such as the Taguchi method, grey relational analysis and artificial neural networks have also been applied in similar optimisation studies [8]. However, CCD was selected here for its ability to efficiently explore factor interactions and curvature effects in the response surface. The independent variables selected for optimisation were pyrolysis temperature (ranging from 400 to 550 °C) and residence time (ranging from 120 to 210 min). These parameters were chosen based on their pronounced influence on thermochemical conversion performance and their potential for industrial-scale adjustment.

The CCD matrix comprised 13 experimental runs, including five replicates at the central point to assess experimental error, four factorial points to capture linear and interaction effects and four axial points to probe curvature in the response. The experiments that were not part of the central point are not replicated. However, this balanced design ensured that the quadratic regression model would be robust and capable of accurately describing the process. All statistical analysis and model development were conducted using Design-Expert software (Stat-Ease, USA), which provided a reliable computational environment for process optimisation and decision making.

2.3 Experimental procedure

The co-pyrolysis experiments were conducted in a custom-built, two-stage fixed-bed reactor system. The configuration included a main pyrolysis chamber fabricated from stainless steel (length of 150 mm, wall thickness of 10 mm, height of 470 mm and maximum capacity of 500 g) and an integrated long-bed catalytic insert (LFCi) designed to hold dolomite pellets for catalytic upgrading (Fig. 1). The LFCi, also constructed from stainless steel, had an internal diameter of 26.6 mm, a wall thickness of 5 mm and a height of 410 mm. For each run, 500 g of MSW was placed in the pyrolysis chamber and an equal mass of dolomite catalyst was loaded into the LFCi. Prior to heating, the entire system was purged with high-purity nitrogen to eliminate residual oxygen and establish an inert atmosphere, thereby preventing oxidative side reactions. Heating was performed using an electric furnace coupled with a digital temperature controller with ± 1 °C accuracy, at a heating rate of 7 to 8 °C/min. The residence time was recorded from the moment the target temperature was reached.

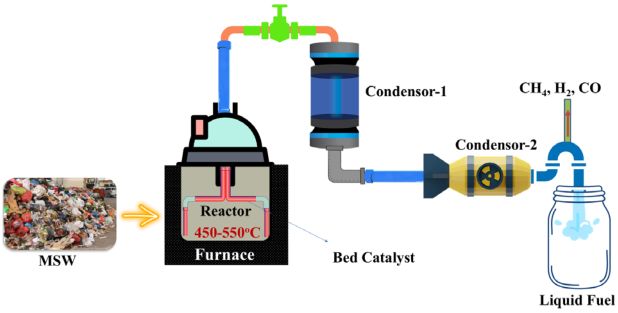

Figure 1. Experimental apparatus for co-pyrolysis

The volatile products generated during pyrolysis passed through a two-stage condensation system consisting of a water-cooled condenser (25 – 30 °C) followed by a refrigerated condenser (5 – 10 °C). This arrangement efficiently separated the condensable liquid fraction from the non-condensable gases. Biochar was collected from the reactor base after cooling, while the liquid fraction was stored in sealed glass vials for analysis. The syngas fraction was flared immediately to avoid environmental release.

2.4 Product characteristics and statistics analysis

To comprehensively evaluate the physicochemical quality and energy potential of the liquid fuel produced, a set of standardised analytical procedures was performed. The kinematic viscosity was determined following the ASTM D445 standard using a Cannon-Fenske viscometer. Fuel density was assessed in accordance with ASTM D4052, employing an Anton Paar DMA 4100 density meter. The higher heating value (HHV), representing the energy content of fuel, was quantified through bomb calorimetry using the ASTM D5865 method. These combined measurements provided a detailed and reliable characterisation of the fuel's physical and thermal properties, enabling assessment of its suitability for practical energy applications.

Further, a quadratic regression model was developed to mathematically represent the relationships between input factors and output responses. These relationships were expressed as second-order polynomial equations, enabling systematic evaluation of both main effects and interaction terms. Model validation included a detailed analysis of variance (ANOVA), examining coefficients of determination (R^2 and adjusted R^2), p-values and conducting a lack-of-fit test to confirm that the regression equations accurately reflected the examined data. Furthermore, the synergistic effect of the co-pyrolysis process was examined by comparing the actual yield with the theoretical yield, which was calculated based on the individual pyrolysis performance of each feedstock fraction. Response surface plots were also interpreted to visualise the interaction between variables and to delineate the optimal operational domains within the design space.

3. Results and discussion

3.1 Influences of temperature and residence time on liquid fuel productivity

The experimental results summarised in Table 1 demonstrate a clear dependency of liquid fuel yield (LF) on both pyrolysis temperature and residence time during the co-pyrolysis of MSW. At the lowest experiment condition at 400 °C with a residence time of 120 minutes, the liquid yield was limited to 10.1 wt. %. In contrast, increasing the temperature to 500 °C and extending the residence time to 210 minutes enhanced the yield to 30.8 wt. %. This substantial increase confirms previous findings that high temperatures accelerate thermal decomposition and increase the evaporation of organic matter in the feedstock, thereby increasing the proportion of condensable products [9]. The noticed trends reflect the dual role of temperature in facilitating primary decomposition and the release of volatile intermediates. Temperature also poses a risk of triggering secondary cracking when raised above the optimal threshold. Similarly, residence time acts as a critical control variable, affecting the rate of these reactions. Longer residence times allow for more complete primary conversion, but can also induce excessive cracking or polymerisation, both of which can reduce fluid yield and alter fuel quality.

The data also show that the interaction between temperature and residence time is additive rather than synergistic within the studied range. This implies that each factor can be optimised independently without significant loss of process efficiency. This observation is consistent with the report by Chen et al. [10], who found minimal interactive effects between operational parameters in MSW pyrolysis systems. Figure 2 illustrates a strong correlation between the

Table 1. CCD results

Run	Input factor		Output response			
	A: temperature, °C	B: residence time, min	liquid fuel yield, wt. %	higher heating value, kcal/kg	viscosity, mm^2/s	density, g/cm^3
1	400	210	18.5	9756	3.06	1.0260
2	450	150	25.4	9856	5.35	0.9037
3	450	210	30.3	9978	3.25	0.9745
4	400	120	10.1	9140	3.22	1.0782
5	500	120	25.4	9233	4.93	1.0152
6	400	150	12.2	9356	3.51	0.9966
7	450	150	25.2	9792	5.35	0.9818
8	450	150	27.6	9836	5.89	0.9973
9	450	150	24.2	9788	5.99	0.9649
10	500	210	30.8	9937	4.61	0.9630
11	450	150	22.8	9597	5.83	1.0165
12	450	120	19.3	9249	4.03	1.0267
13	550	180	27.4	9247	5.81	0.8761

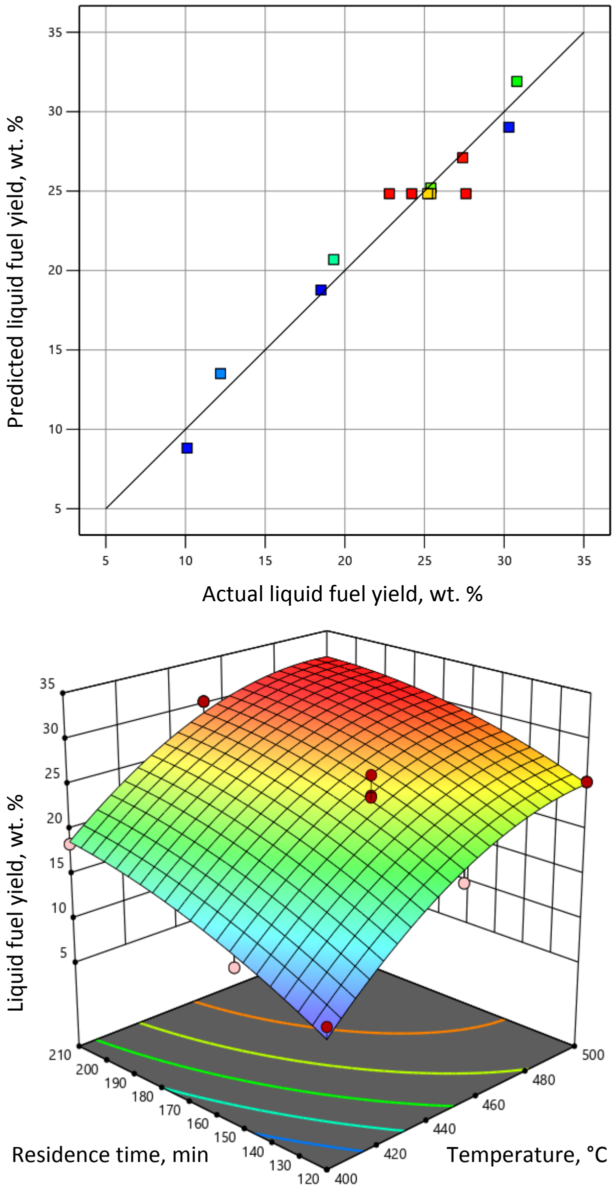

Figure 2. Comparison of the actual and predicted liquid fuel yield values and 3D response surface analysis based on CCD

predicted and experimental (actual) results, which confirms the robustness of the quadratic regression model developed in this study. The reliability of the model is supported by a high coefficient of determination (R^2 = 0.9571) and a low coefficient of variation (CV = 7.52 %), and it shows consistent and reproducible results. The optimal condition, as shown in Figure 2, occurs at a temperature of 488.2 °C with a residence time of 202.1 minutes, resulting in a maximum yield of 31.8 wt. % and an HHV of 9978 kcal/kg, with properties comparable to commercial diesel fuel.

3.2 Statistical analysis of liquid fuel productivity

The statistical robustness of the developed quadratic model can be used to predict the LF from MSW co-pyrolysis, which is well validated through an ANOVA test, as shown in Tables 2 and 3, where the model shows excellent significance with an F-value of 31.26 and a p-value of 0.0001. These values confirm that the selected independent variables (temperature and residence time) substantially affect the obtained responses. A high coefficient of determination (R^2 = 95.71 %) indicates that the model accounts for most of the variation in the LF. Meanwhile, the adjusted R^2 (92.65 %) and predicted R^2 (82.29 %) further confirm that the model's robustness and predictive reliability exceed the limits of the experimental data set. In addition, an adequate precision ratio of 19.63 reflects a superior signal-to-noise ratio, and a CV of 7.52 % underscores the stability and reproducibility of the experimental results. This level of model performance is in line with the findings of Nawaz et al. [11], who also showed the strong predictive capacity of RSM in pyrolysis systems.

Table 2. ANOVA for the quadratic model for liquid fuel yield

Source	Adjusted sum of squares	Degree of freedom	Adjusted mean square	F-value	p-value	Factor effect
Model	468.50	5	93.70	31.26	0.0001	significant
A	335.34	1	335.34	111.87	< 0.0001	
B	104.87	1	104.87	34.99	0.0006	
A × B	2.66	1	2.66	0.8860	0.3779	
A × A	127.61	1	127.61	42.57	0.0003	
B × B	5.75	1	5.75	1.92	0.2085	
Residual error	20.98	7	3.00			
Lack-of-fit	8.55	3	2.85	0.9170	0.5087	not significant
Pure error	12.43	4	3.11			
Cor total	489.48	12				

Table 3. Fit statistics for liquid fuel yield

Parameter	Value
Standard deviation, wt. %	1.73
Mean value, wt. %	23.02
CV, %	7.52
R^2	0.9571
Adjusted R^2	0.9265
Predicted R^2	0.8229
Adequate precision	19.6289

Among the variables tested, temperature appears to be the most dominant factor with an F-value of 111.87 (p-value < 0.0001). This indicates the important role of temperature in encouraging thermal degradation paths. High thermal conditions accelerate damage to the structure of polymers and evaporation of organic matter, which affects the increase in liquid fuel yield. This observation is strengthened by several studies that have identified the optimal temperature range (usually between 400 and 550 °C) to maximise the product that can be condensed before further degradation becomes permanent gas. Conversely, although the residence time was also statistically significant (F-value = 34.99, p-value = 0.0006), its role was relatively less influential. Inadequate residence time can inhibit complete pyrolytic conversion, and excessive duration is at risk of triggering secondary reactions that reduce liquid fuel yield [12,13].

Interestingly, the interaction (A × B) is statistically insignificant (F-value = 0.8860, p-value = 0.3779), which shows that the temperature and time of residence independently affect liquid results without important synergistic effects. This finding is in harmony with the conclusions from Chen et al. [10] and Hasan et al. [3], who reported that in heterogeneous raw materials such as MSW, parameter interactions often contribute to a minimum variation of results. The quadratic effect of temperature (A × A) was significant to the liquid fuel yield result, whereby a F-value of 42.57 (p-value = 0.0003) shows a nonlinear relationship in the form of a bell curve. Such a pattern reflects the optimal temperature, and above will trigger the thermal over-cracking and gas formation, thereby reducing the liquid fraction. Conversely, the quarterly effect of residence time (B × B) was not statistically significant (F-value = 1.92, p-value = 0.2085), implying the effect is predominantly linear in the tested range.

The reliability of the model is subsequently confirmed by the lack-of-fit test (F-value = 0.9170, p-value = 0.5087), which reveals that the residual variation is more random than systematic variations. Figure 2 supports this by showing the high correlation between the experimental (actual) and predicted liquid fuel yield results. It also visualises the surface of the three-dimensional response that describes the optimal results at around 500 °C and 210 minutes. The regression equation derived from the results of the ANOVA analysis represents the optimised model, as follows.

$$LF = -401.01356 + 1.53260\,T + 0.505949\,t - \\ -0.000360\,Tt - 0.001473\,T^2 - 0.000762\,t^2, \quad (1)$$

where *LF* is liquid fuel yield in wt. %, *T* is temperature in °C and *t* is residence time in minutes.

This equation effectively captures temperature and residence time interactions and offers a valuable predictive tool to improve MSW pyrolysis conditions.

3.3 Influences of temperature and residence time on liquid fuel properties

The properties of liquid fuel produced through co-pyrolysis of MSW were substantially influenced by operational conditions such as temperature and residence time. As detailed in the results of ANOVA (Table 4), these parameters significantly affected the fuel heat values, viscosity and density. This finding underlines the importance of regulating the appropriate temperature and time duration to obtain the characteristics of fuel that are compatible with industrial applications.

For the higher heating value, the residence time gives a more substantial effect (F-value = 62.65, p-value < 0.0001) than the temperature (F-value = 3.83, p-value = 0.0912). This emphasises the role of a long-time duration, facilitating the complete decomposition of organic material into energy-rich compounds. However, these two parameters show a significant quadratic effect, which proves the optimal point. Beyond this point, fuel quality can decrease due to secondary reactions such as polymerisation and light hydrocarbon fragmentation [14].

In the case of viscosity, temperature appears as a primary influencing factor (F-value = 22.90, p-value = 0.0020), followed by the quadratic effect of residence time (p-value = 0.0019). Increased levels of temperature and expanded residence time tend to support aromatic formation with higher molecular weight and cause an increase in fluid

Table 4. ANOVA for the quadratic model for output responses

Source	Adjusted sum of squares	Degree of freedom	Adjusted mean square	F-value	p-value	Factor effect
Higher heating value						
Model	1.05×10^6	5	2.10×10^5	18.89	0.0006	significant
A	4.26×10^4	1	4.26×10^4	3.83	0.0912	
B	6.96×10^5	1	6.96×10^5	62.65	< 0.0001	
A × B	504.03	1	504.03	0.0454	0.8374	
A × A	4.62×10^5	1	4.62×10^5	41.58	0.0004	
B × B	8.62×10^4	1	8.62×10^4	7.75	0.0271	
Residual error	7.78×10^4	7	1.11×10^4			
Lack-of-fit	3.54×10^4	3	1.18×10^4	1.11	0.4425	not significant
Pure error	4.24×10^4	4	1.06×10^4			
Cor total	1.13×10^6	12				
Viscosity						
Model	13.60	5	2.72	10.94	0.0033	significant
A	5.69	1	5.69	22.90	0.0020	
B	0.2805	1	0.2805	1.13	0.3233	
A × B	0.0449	1	0.0449	0.1806	0.6836	
A × A	1.13	1	1.13	4.53	0.0707	
B × B	5.84	1	5.84	23.51	0.0019	
Residual error	1.74	7	0.2485			
Lack-of-fit	1.36	3	0.4530	4.76	0.0829	not significant
Pure error	0.3805	4	0.0951			
Cor total	15.34	12				
Density						
Model	0.0256	5	0.0051	4.42	0.0389	significant
A	0.0067	1	0.0067	5.77	0.0474	
B	0.0043	1	0.0043	3.72	0.0952	
A × B	7.92×10^{-6}	1	7.92×10^{-6}	0.0068	0.9365	
A × A	0.0000	1	0.0000	0.0089	0.9274	
B × B	0.0086	1	0.0086	7.37	0.0300	
Residual error	0.0081	7	0.0012			
Lack-of-fit	0.0007	3	0.0002	0.1249	0.9405	not significant
Pure error	0.0074	4	0.0019			
Cor total	0.0338	12				

viscosity. These results are consistent with the previous report on the pyrolysis of complex raw materials, which connects thermal severity with long-chain hydrocarbon enrichment and polycyclic aromatic hydrocarbons in the liquid phase [15-17].

Regarding density, the temperature also shows a significant effect (F-value = 5.77, p-value = 0.0474), while the residence time has a lower but prominent impact (F-value = 3.72, p-value = 0.0952). The duration of heating and moderate reactions produces fuel with a density that is close to conventional petroleum fuels. Such results validate the potential for the application of pyrolytic liquid in a standard combustion engine [1]. The regression model produces a high determination coefficient (R^2 = 0.9310 for higher heating value and 0.8866 for viscosity), which confirms their ability to predict experimental trends accurately (Table 5).

Table 5. Fit statistics for liquid fuel properties

Parameter	Value
Higher heating value	
Standard deviation, wt. %	105.42
Mean value, wt. %	9597.31
CV, %	1.10
R^2	0.9310
Adjusted R^2	0.8817
Predicted R^2	0.6999
Adequate precision	13.5796
Viscosity	
Standard deviation, wt. %	0.4985
Mean value, wt. %	4.68
CV, %	10.65
R^2	0.8866
Adjusted R^2	0.8056
Predicted R^2	0.2034
Adequate precision	9.4377
Density	
Standard deviation, wt. %	0.0341
Mean value, wt. %	0.9862
CV, %	3.45
R^2	0.7593
Adjusted R^2	0.5874
Predicted R^2	0.4283
Adequate precision	8.2147

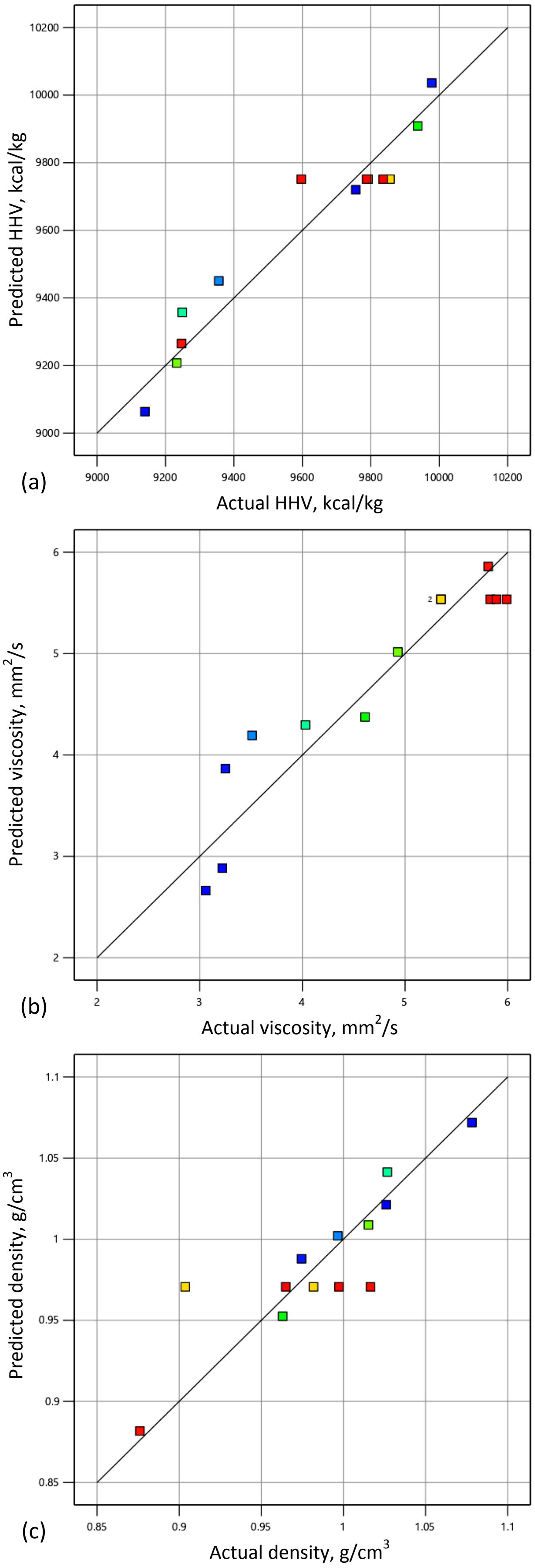

Figure 3. Comparison of the actual and predicted property values: (a) higher heating value (HHV), (b) viscosity and (c) density

Although the density model exhibited a comparatively lower R^2, it still provided satisfactory predictive alignment. This is illustrated in Figure 3, where actual and predicted values show high conformance, indicating robust model performance. Nonetheless, deviations in the predicted R^2 for viscosity (0.2034) and density (0.4283) highlight the potential influence of unaccounted variables such as heating rate and feedstock heterogeneity. Future studies should incorporate these factors to refine model accuracy.

Surface plots (Fig. 4) reveal that optimal values were achieved near 500 °C with 210 minutes residence time, reflecting intensified aromatisation and formation of medium-chain hydrocarbons. Likewise, viscosity peaks within the 450 – 500 °C range under moderate residence times, corroborating the formation of denser, aromatic compounds. The noticed decline in density with increasing temperature and residence time suggests a transition toward lighter hydrocarbon fractions,

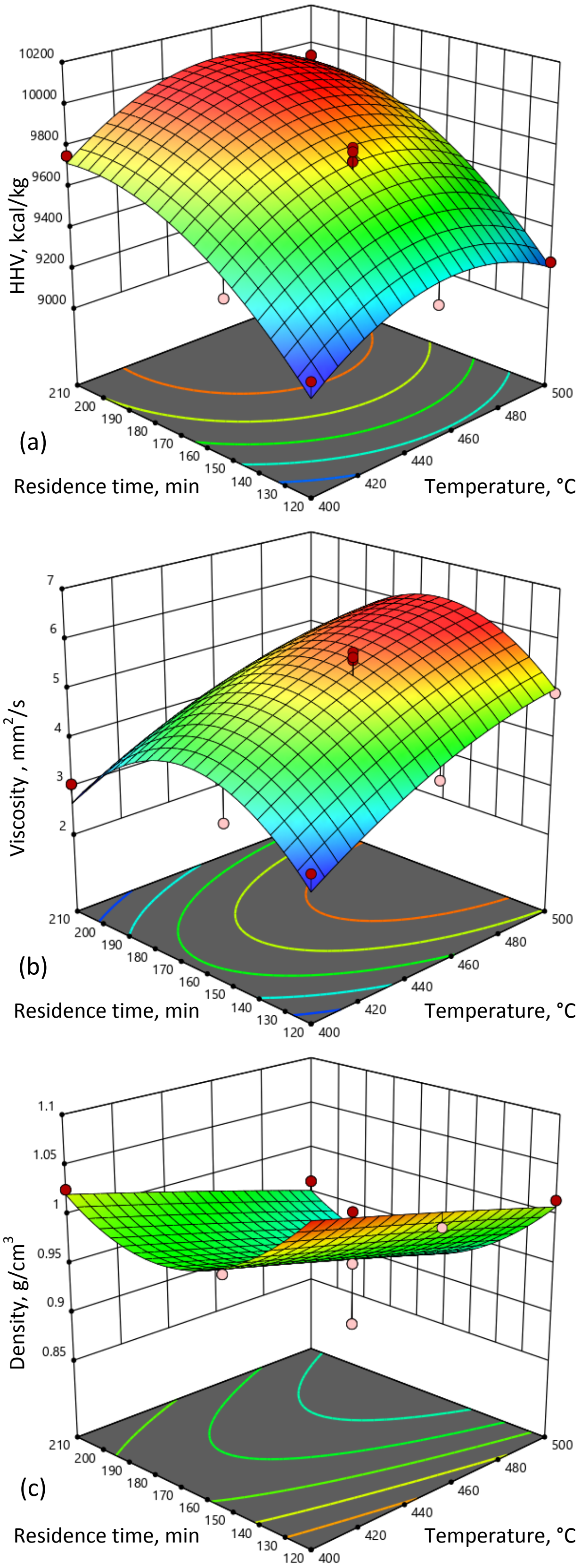

Figure 4. Effect of temperature and residence time on: (a) higher heating value (HHV), (b) viscosity and (c) density

which is desirable for fuel formulations targeting diesel or gasoline standards [18,19]. The regression equations representing the relationship between process variables and fuel properties are as follows.

$$HHV = -12{,}229.11437 + 80.62002\,T + 36.10515\,t + \\ +0.004954\,Tt - 0.088639^2 - 0.093303\,t^2, \quad (2)$$

$$v = -64.64089 + 0.151514\,T + 0.269782\,t - \\ -0.000047\,Tt - 0.000138\,T^2 - 0.000768\,t^2, \quad (3)$$

$$\rho = 2.01913 - 0.000179\,T - 0.010017\,t - \\ -6.20888 \cdot 10^{-7}\,Tt - 4.19694 \cdot 10^{-7}\,T^2 + \\ +0.000029\,t^2, \quad (4)$$

where *HHV* is higher heating value in kcal/kg, *v* is viscosity in mm^2/s and *ρ* is density in g/cm^3.

The regression models developed for higher heating value and viscosity exhibited exceptionally high coefficients of determination (R^2 = 0.9310 and 0.8866, respectively), as presented in Table 5. These values confirm that temperature and residence time were successfully calibrated within the models to yield highly accurate predictions in line with the experimental results. Although the coefficient of determination for density was comparatively lower, the model still demonstrated a satisfactory level of accuracy. Furthermore, Figure 3 illustrates a comparative analysis between the predicted and actual values for the key parameters: higher heating value, viscosity and density of the resulting liquid fuel. Visually, the scatter plots display a strong alignment of data points along the diagonal line (*y* = *x*), with minimal deviation, signifying a high degree of conformity between the regression outputs and the obtained data.

3.4 Multi-response optimisation using overall desirability function

The integration of the desirability function technique (DFT) for multi-response optimisation in MSW co-pyrolysis has yielded highly effective results. This approach enables simultaneous optimisation of several critical responses, such as liquid fuel yield, higher heating value, viscosity and density within a single statistical framework. The achieved overall desirability score of 0.747 at optimal conditions (488.2 °C and 202.1 minutes) illustrates a strong compromise among the targeted responses, indicating a well-balanced operational strategy (Table 6). The optimal liquid fuel yield of 31.76 wt. % significantly surpasses benchmarks reported in similar studies, such as Anuar Sharuddin et al. [20], who noted maximum yields of approximately 25 – 30 wt. % at comparable temperatures. The corresponding higher heating value of 9977.99 kcal/kg ranks the fuel within the energy spectrum of conventional gasoline, reinforcing its viability for combustion-based applications [21]. Meanwhile, the viscosity of 4.869 mm^2/s and density of 0.947 g/cm^3 closely align with standard diesel specifications [22,23], confirming the fuel's practical suitability.

Table 6. Multi-response optimisation results

Parameter	Value
Temperature, °C	488.2
Residence time, min	202.1
Liquid fuel yield, wt. %	31.76
Higher heating value, kcal/kg	9977.9
Viscosity, mm^2/s	4.87
Density, g/cm^3	0.947
Desirability	0.75

DFT effectiveness lies in its capacity to consolidate diverse performance metrics into a unified desirability index. In this study, yield and higher heating value were optimised using a larger-is-better criterion, while viscosity and density were optimised under a nominal-is-best approach. This methodology aligns with best practices in multi-response optimisation and has been proven in various engineering applications to outperform single-response strategies [24,25]. The achieved desirability score also surpasses previously reported benchmarks, such as the 0.68 score obtained by Makkawi et al. [26] in plastic pyrolysis systems, underscoring the efficiency of the present optimisation scheme even when applied to highly heterogeneous feedstocks. The results not only validate the methodology but also provide actionable guidance for scaling up pyrolysis systems for urban waste management. In conclusion, the DFT-based optimisation approach effectively harmonises multiple process targets, yielding a pyrolytic liquid fuel that satisfies both energy performance and physical property criteria. Its application provides a strategic advantage for MSW valorisation, bridging the gap between laboratory-scale trials and industrial-scale implementation.

In addition, the interaction between temperature and residential time shows a significant and diverse effect on the properties of liquid fuel derived from MSW. In the model, the negative interaction coefficient (– 0.000360) indicates that the combination of further increase in temperature and residence time can reduce liquid fuel yields due to an increase in secondary crack reactions that support the formation of gas products. Conversely, the coefficient of positive interaction noticed in the higher heating value model (0.004954) indicates that a balanced synergy between temperature and residential time can significantly increase the energy content of the fuel produced. This phenomenon correlates with the findings of previous studies [5,27], which also show that the interaction of the optimised temperature and residence time can significantly improve the energy density of the pyrolysis-derived liquid fuel.

4. Conclusion

This study presents a systematic approach using statistical science to optimise the co-pyrolysis of municipal solid waste into high-quality liquid fuel using response surface methodology and desirability function technique.

The work aimed to reveal the individual effects and interactions of temperature and residence time on the liquid fuel yield and its properties. The optimal values were obtained at 488.2 °C and 202.1 minutes, which gave a liquid fuel yield of 31.76 wt. % with a high energy density value of 9977.9 kcal/kg, which is very similar to the characteristics of commercial diesel oil. The analysis revealed that temperature was more dominant in controlling the liquid fuel yield, while residence time had a stronger influence on the energy density value. Viscosity and density were also significantly affected by these parameters, and the optimal conditions obtained properties that are within the range of standard diesel fuel.

The desirability score of 0.75 obtained by the desirability function technique confirms that the optimised process achieves a strong balance between liquid fuel yield, energy density and physicochemical properties comparable to other optimisation studies, even in the context of the inherent heterogeneity of municipal solid waste. In addition to laboratory-scale validation, the proposed optimisation framework offers practical scalability and local applicability, allowing process configurations to be tailored to specific regional conditions.

To strengthen these scientific findings, integrated controls based on IoT (Internet of Things) and optimisation to compensate for the feedstock variability in real-time are highly recommended. This advancement will not only improve operational efficiency but also accelerate the transition towards sustainable waste-to-energy solutions, contributing to low-carbon energy systems and sustainable municipal waste management.

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