

RESEARCH ARTICLE

Comparison of the combustion characteristics and kinetic study of coal, municipal solid waste, and refuse-derived fuel: Model-fitting methods

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Abstract

Energy crisis and solid waste management have remained challenging issues for authorities in Pakistan. These issues tend to rise with increasing population and economic growth of the society. Therefore, environmentally sustainable waste-to-energy program must be part of the waste management system since they may substitute fossil fuels with renewable energy sources by enabling energy recovery instead of landfill of solid wastes. In this work, the combustion characteristics of fossil fuel (coal) and solid wastes such as municipal solid waste (MSW) and refuse-derived fuel (RDF) were investigated by thermogravimetric analysis (TGA) to compare their thermal decomposition behavior. Furthermore, proximate and ultimate analyses of these samples were carried out along with their heating values. The TGA profiles of samples indicate low reactivity of coal, whereas solid wastes present greater reaction rate reflecting their low ash and high volatile contents. It was found that the heating value of RDF sample was close to that of coal. The obtained thermal data were used to calculate the kinetic parameters using Arrhenius and Coats-Redfern models with different reaction mechanisms. According to these models, the fuels could be arranged in order of activation energy as coal > RDF > MSW. The percentage difference between activation energy values found from Arrhenius and Coats-Redfern models was in the range of 4.1%-26.5%. However, the Coats-Redfern model exhibited consistency in activation energy values, followed by a high value of R^2 . These results of the TGA could be very helpful to predict the combustion dynamics and confirm that MSW and RDF may be used as sustainable fuels, to meet the prevailing challenges of the energy crisis and solid waste management.

KEYWORDS

combustion, model fitting, municipal solid waste, RDF, renewable energy, waste-to-energy

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1 | INTRODUCTION

The abrupt rise in population and industrial development has brought many challenges, related to energy security and environmental issues, especially in developing countries. The increasing energy issues and concerns about the future supply and demand have marked it as an extensively discussed subject. According to the international energy outlook 2017, world energy demand is expected to increase by 28% between the period of 2015 and 2040, with more demand share from Asia.¹ The 1.2 billion of the world population still have no access to energy, which is even lesser than the last estimated value of 2013.² According to the International Energy Agency (IEA), Pakistan has total primary energy supply (TPES) demand of 93.91 Mtoe, while the total energy production is 70.94 Mtoe.³ Due to this considerable energy gap between supply and demand, there is a dire need to add more options for energy generation, to deal with the energy crisis in Pakistan.

To meet with the world energy demand, coal and biomass are the first and third dominant energy sources.⁴ In the foreseeable future, most of the countries will continue with their coal power generation facilities, due to abundantly and cheaply available coal source. Pakistan has enormous 185 billion tons of coal reserves. The country has 1.45 thousand Mtoe of recoverable coal reserves with a coal production capacity of 2.33 Mtoe/y.⁵ Utilization of fossil fuels such as coal for energy production can contribute to serious environmental issues, as combustion of coal represents the main contribution to anthropogenic CO₂ emission.⁶ The increasing awareness level to the climate changes, environmental protection rules, and regulations are the major reasons for the growing interest in renewable energy sources and carbon capture and storage (CCS) technologies.⁷ Renewable energy sources are expecting the growth rate from 3% in 2015 to 10% in 2035.⁸

At present, Pakistan is facing serious environmental and social issues, which are linked with mismanagement of municipal solid waste (MSW). Growing population, rapid urbanization, and improvement in living standards of the community have accelerated generation rate of MSW.⁹ Annually, approximately 32.0 million tons of MSW is being generated in major cities of the country.¹⁰ The estimated amount of methane emission from landfills in Pakistan is 14.18 Gg/y. This release of methane to atmosphere traps the heat and has a 22-fold greater greenhouse effect than CO₂.¹¹ Thus, it is of vital importance to adopt a suitable strategy to address the issue of methane emission from landfills. In most of the developing countries, dedicated municipalities for waste management are unable to provide an efficient system to address the issue of uncontrolled waste.¹² Many factors such as financial resources, legislation, lack of technical training capabilities in the organization, lesser political will and unavailability of engineered landfills, and processing and

collection equipment are the most common associated reasons for mismanagement of MSWs. This leads to degradation of the environment and ultimately public health.^{10,13,14}

Nowadays, issues of energy crisis and mismanagement of the MSW have acquired alarming aspect in the country. Worldwide, four methods of MSW disposal are landfilling, composting, dumping into sea, and incineration.¹⁵ The use of MSW and RDF as fuel can assist in addressing the energy issues, especially for those countries having resources. The RDF is mechanically separated and processed a combustible fraction of MSW. This processing results in more predictable properties of RDF with the high heating value and makes it better fuel compared to other biowaste fuels. In developed countries, the incineration of RDF has been practiced to solve the waste and energy issues simultaneously.¹⁶ Based on the principle of reduction, recycling, and harmless, incineration is a widely used method to attain efficient use of MSW and refuse-derived fuels (RDFs) as an alternative renewable energy source.¹⁷⁻²⁰

To assess the performance of different thermochemical conversion processes, it is essential to have good knowledge of thermal decomposition mechanism and kinetic parameters for solid fuels.²¹ Thermal analysis or thermogravimetric analysis (TGA) is extensively used technique to analyze the decomposition mechanism. Ultimately, researchers have used TGA data for the determination of kinetic parameters to develop kinetic models, which helps in the quantitative description of different thermochemical conversion processes.^{17,22-26} The two main difficulties in developing kinetic models are involvement of parallel and multiseried decomposition reactions and the heterogeneous nature of solid fuel particles during decomposition process. This fact has motivated the researchers to develop more accurate models to explain the kinetic behavior during the decomposition of solid fuels. This effort has led to the formation of two groups of model, model fitting, and model-free or isoconversional models.²⁷⁻²⁹ In model-fitting approach, different reaction mechanisms are applied to TGA/DTG data and a model performing comparatively better fit is considered a suitable model for determination of kinetic parameters, whereas in the model-free approach, the kinetic data are extracted by the use of developed mathematical relations, without the consideration of reaction mechanism.³⁰⁻³² Different researchers have made use of individual model from both groups or have done a comparison of models from both groups, for accurate determination of kinetic parameters for coal and solid wastes.³³⁻³⁵ The number of studies on kinetic modeling and decomposition behavior of complex heterogeneous solid wastes such as MSW and RDF at single slot is very rare.²²

The aim of this study is to highlight the potential of abundantly available MSW and RDF as alternative energy sources to promote effective waste management, compared to pollution imparting energy source of coal. In this respect, the

additional added value of this study is based on the selection of MSW and RDF as sustainable alternative energy source. For this purpose, thermal decomposition and combustion kinetic analysis for coal, MSW, and RDF have been performed with four heating rates (10, 20, 30, and 40°C/min) to check the applicability of Arrhenius and Coats-Redfern model in model-fitting category.

2 | MATERIALS AND METHODS

Coal sample was taken from Chiragh coal reserves located in the province of Punjab, Pakistan. For a good representative sample of MSW, the social and economic structure at 12 different towns of the city of Lahore, Pakistan, was taken into consideration. Based on the average generation rate of MSW (ie, 0.65 kg/capita/d), the daily production of MSW in this city would reach 7150 tons/d. The “U.S standard ASTM D5231” and “European Commission Methodology for the Analysis of Solid Waste” were used as the basis for physical characterization of waste. According to spot sampling method, a total of 12 homogenized samples of MSW were collected from 12 MSW carrying trucks (capacity ~ 6000 kg/truck). With the assumptions of average waste generation rate of 0.65 kg/capita/d and family size of seven persons, each truck represents a waste of 190 houses from one location. The shovel technique was used instead of the quartering method due to the size of the samples. Physical characterization was carried out with a sample of 0.5 m³ from homogenized MSW from each truck by using a scale container. The average composition of MSW from different socioeconomic levels of Lahore is shown in Figure 1. The physical components of MSW in Lahore were found to be in the descending order of biodegradable, nylon plastic bags, textile, diaper, and paper. The high amount of biodegradables, especially food residue, would result in a high moisture content in the MSW. The high percentage of nylon plastic bags in MSW is alarming and a great environmental threat. For a better understanding

of variation in MSW and RDF compositions (chemical characterization), five major combustible fractions of MSW including biodegradable, nylon plastic bags, textile, PET, and paper, which represent 81% of total MSW, were selected and subjected to individual proximate and ultimate analyses and heating value test according to the respective ASTM standards. The fractions such as glass, metal, and inert were not considered for this study. Prior to testing, all samples were oven-dried at 105°C for 6 hours. The coal and MSW fractions were ground to a size less than 200 µm. For size reduction of MSW fractions, double milling action with nitrogen support was used. The samples of MSW and RDF were prepared by mixing of true combustible fractions according to the component proportion in physical characterization data, as represented in Table 1. To ensure uniform mixing of different fractions, a rotary mixer rotated at a speed of 25 rpm for 2.5 hours was used. Test for energy content and ultimate analysis for all samples was done by using a bomb calorimeter (IKA C 2000) and elemental analyzer (2400 CHN; PerkinElmer), respectively, as shown in Table 2.

Thermogravimetric experimental runs were performed in Mettler Toledo System (TGA/DSC 1 STAR) with sample size of 20 mg. The samples were heated from 25°C to 105°C at a heating rate of 10°C/min with holding time of 10 minutes at 105°C. Four heating rates (10, 20, 30, and 40°C/min) were used from 105°C to 1000°C with holding time of 30 minutes at 1000°C. Constant flow rate (80 mL/min) of synthetic air was provided for all experimental runs.

2.1 | Kinetic modeling

The rate of reaction for solid fuel is written as:

$$d\alpha/dt = f(T) \times f(\alpha) \quad (1)$$

$$\text{where } f(T) = Ae^{-\frac{E}{RT}} \quad (2)$$

and α known as a fractional conversion is given as:

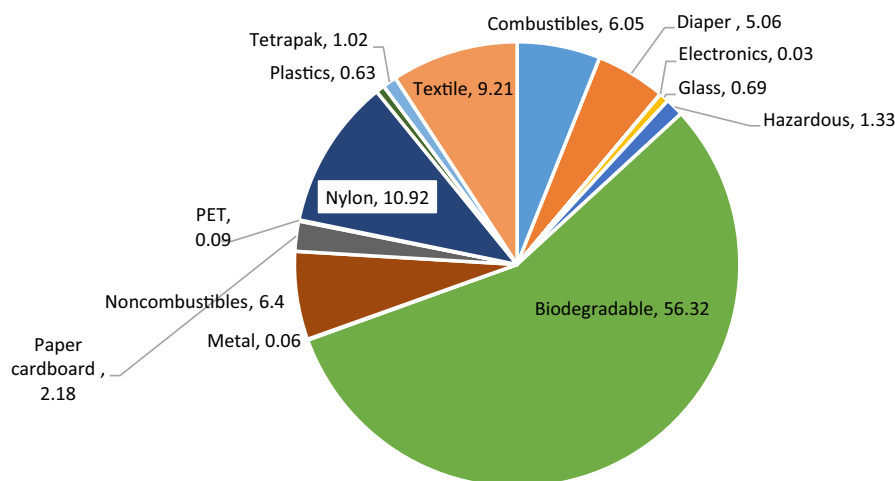


FIGURE 1 Physical percentage composition (average) of Lahore MSW

TABLE 1 Composition (weight percentage basis) of MSW and RDF

Components	Biodegradable	Textile	Nylon plastic bags	Paper	PET bottles
MSW	69.1	11.5	14.5	4	0.9
RDF	–	37.6	47.3	13.3	1.8

TABLE 2 Proximate and ultimate analyses of samples

Samples	Proximate analysis ^a				Ultimate analysis ^b					
	H ₂ O (%)	VM (%)	Ash (%)	F.C ^c (%)	C (%)	H (%)	O ^c (%)	N (%)	S (%)	HHV (kJ/kg)
Biodegradable	4.1	77.5	10	8.4	62.5	8.0	28.8	0.4	0.1	10 338
Textile	2.94	81.23	5.01	10.82	58.4	4.98	35.7	0.6	0.16	20 392
Nylon plastic bags	0.02	93.71	5.52	0.741	78.7	12.4	8.7	0.12	0.02	40 416
Paper	3.44	75.85	18.82	1.89	50.5	6.41	42.3	0.22	0.55	16 239
PET bottles	ND	92.26	0.19	7.55	62.0	4.04	33.9	0.05	0.01	23 060
MSW	3.3	79.7	9.1	7.2	63.6	8.1	27.1	0.4	0.11	15 978
RDF	1.6	86.2	7.07	4.7	66.9	8.7	23.8	0.32	0.14	29 429
Coal	1.84	38.8	31.7	27.53	80.7	3.6	9.6	1.02	5.04	30 362

^aAir-dried basis.^bDried ash-free basis.^cCalculated by difference.

$$\alpha = \frac{m_0 - m_i}{m_0 - m_\infty} \quad (3)$$

where m_0 is initial mass, m_i is instantaneous mass, m_∞ is the final mass of the sample, and $f(\alpha)$ is a function of fractional conversion (α). Its value depends on the conversion mechanism listed in Table 3.

Under constant temperature ramp conditions, Equation (1) can be converted into the following form by using Equation (2):

$$\frac{d\alpha}{dT} = \frac{A}{\beta} e^{-E/RT} f(\alpha) \quad (4)$$

2.2 | Arrhenius model

It is a model-fitting method. In this model, the $f(\alpha)$ function is given as:

$$f(\alpha) = (1 - \alpha)^n \quad (5)$$

where n is the order of the reaction. Equation (5) in combination with Equation (4) yields following expression:

$$\frac{d\alpha}{dT} = \frac{A}{\beta} e^{-E/RT} (1 - \alpha)^n \quad (6)$$

Generally, the plotting method is applied for the determination of the reaction order. Plot of $\ln[da/dT/(1 - \alpha)^n]$ vs $1/T$ yields lines for various values of n . Estimation of activation energy is done from the slope of the line having the highest R^2 value. This model has been applied by many researchers for the determination of kinetic parameters.^{36,37}

2.3 | Coats-Redfern model

It is the most popular model-fitting method first proposed in 1964. It is also known as the integral model-fitting method. It uses asymptotic series expansion for estimation of temperature integral. If,

$$g(\alpha) = \int_0^\alpha \frac{d\alpha}{f(\alpha)} \quad (7)$$

then Equation (4) can be converted to the form given as:

$$g(\alpha) = \frac{A}{\beta} \int_0^T e^{-\frac{E}{RT}} dT \quad (8)$$

where $g(\alpha)$ is the integral reaction model. Its value is dependent on the reaction mechanism followed by fuel. Various conversion mechanism expressions for $g(\alpha)$ are listed in

Mechanism	$f(\alpha)$	$g(\alpha)$	Abbreviation
Power law	$2\alpha^{1/2}$	$\alpha^{1/2}$	P2
Power law	$3\alpha^{2/3}$	$\alpha^{1/3}$	P3
Power law	$4\alpha^{3/4}$	$\alpha^{1/4}$	P4
Avarami-Eroféve	$2(1-\alpha)[- \ln(1-\alpha)]^{1/2}$	$[- \ln(1-\alpha)]^{1/2}$	A2
Avarami-Eroféve	$3(1-\alpha)[- \ln(1-\alpha)]^{2/3}$	$[- \ln(1-\alpha)]^{1/3}$	A3
Avarami-Eroféve	$4(1-\alpha)[- \ln(1-\alpha)]^{3/4}$	$[- \ln(1-\alpha)]^{1/4}$	A4
Contracting sphere	$2(1-\alpha)^{1/2}$	$[1-(1-\alpha)^{1/2}]$	R2
Contracting cylinder	$3(1-\alpha)^{2/3}$	$[1-(1-\alpha)^{1/3}]$	R3
One-dimensional diffusion	$1/2\alpha$	α^2	D1
Two-dimensional diffusion	$[- \ln(1-\alpha)]^{-1}$	$[(1-\alpha) \times \ln(1-\alpha)] + x$	D2
Three-dimensional diffusion—Jander	$\frac{3(1-\alpha)^{2/3}}{[2(1-(1-\alpha)^{1/3})]}$	$[1-(1-\alpha)^{1/3}]^2$	D3
Three-dimensional diffusion—GB	$3/2 \left((1-\alpha)^{-1/3} - 1 \right)$	$1 - \frac{2\alpha}{3} - (1-\alpha)^{2/3}$	D4
First order	$(1-\alpha)$	$-\ln(1-\alpha)$	F1
Second order	$(1-\alpha)^2$	$(1-\alpha)^{-1} - 1$	F2
Third order	$(1-\alpha)^3$	$[(1-\alpha)^{-2} - 1] / 2$	F3

TABLE 3 Expressions for $f(\alpha)$ and $g(\alpha)$ based on various reaction mechanisms²⁸

Table 3. Transformation of Equation (4) using Equation (8) yields following expression of Coats-Redfern model for estimation of kinetic parameters:

$$\ln \left(\frac{g(\alpha)}{T^2} \right) = \ln \frac{AR}{\beta E} \left(1 - 2 \frac{RT}{E} \right) - \frac{E}{RT} \quad (9)$$

For the determination of reaction order, the plot of the left-hand side of Equation (9) vs $1/T$ for each reaction mechanism listed in Table 3 yields approximately straight lines. Activation energy is estimated from the slope of the line having the best fit to the experimental data. This model has widely been used for estimation of the kinetics of solid fuel's reactions.³⁸⁻⁴²

3 | RESULTS AND DISCUSSION

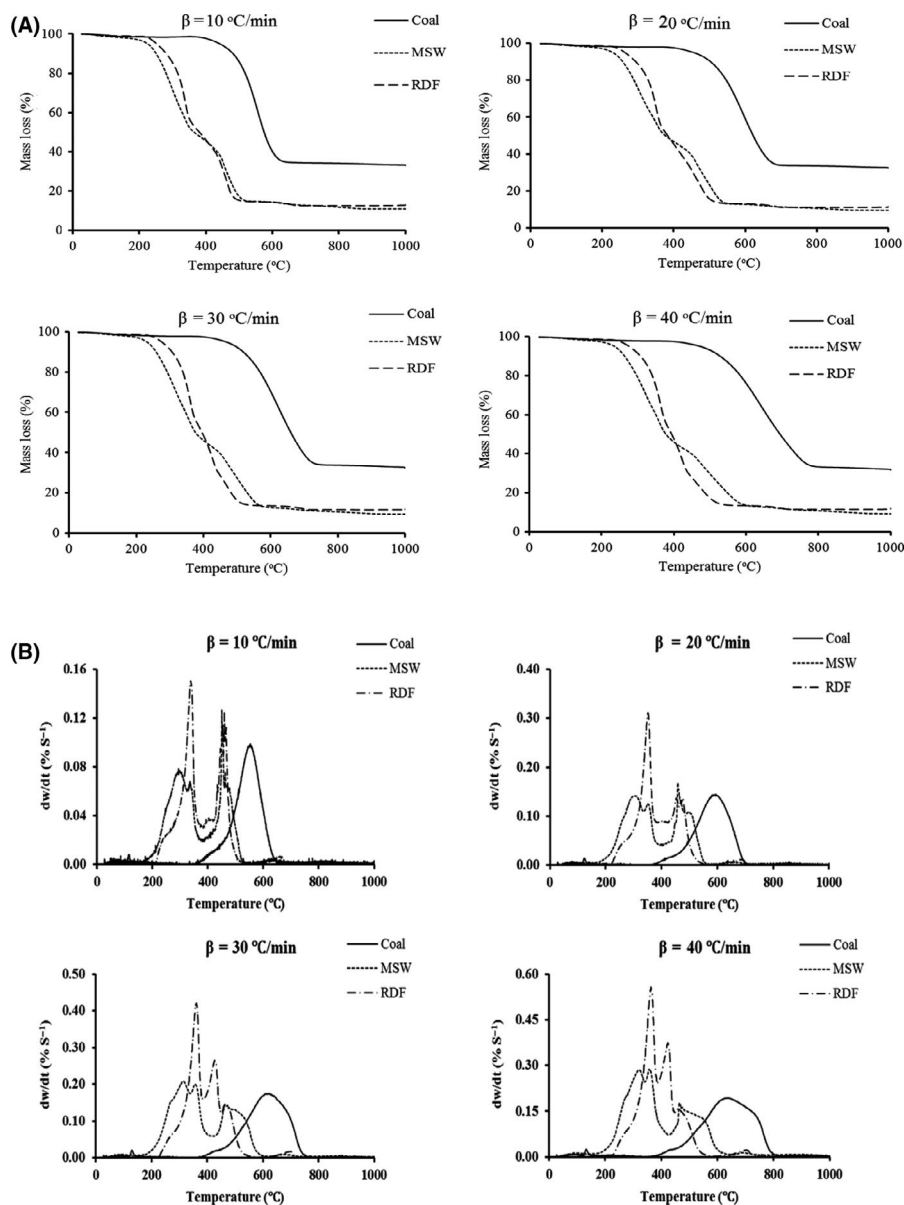
3.1 | Characterization of the raw material

The solid wastes (MSW and RDF) are heterogeneous mixtures, and their composition varies from region to region. Different socioeconomic parameters (population, lifestyle, income per capita, and education) and weather conditions play a significant role in defining quantity and quality of generating wastes. The simulated MSW consists of five true combustible components and contain (mass composition) 69% biodegradable, 14.5% nylon plastic bags, 11.5% textile, 4% paper, and 0.9% PET bottles. Refuse-derived

fuel composition is without biodegradables, derived from the same MSW stream, and contains high percentages of nylon plastic bags (47.3%), textile (37.6%), paper (13%), and PET bottles (1.8%). The results of the proximate analysis show that MSW contains slightly high moisture content than the RDF and coal samples. The volatile matter contents of RDF are higher than those of MSW. The ash content of the fuel is important as it determines the calorific value and amount of residue that will be generated after combustion process.⁴³ Among all samples, coal has the highest ash and fixed carbon content. The results of the ultimate analysis reveal that MSW and RDF have quite close values for carbon, hydrogen, and oxygen contents. The higher oxygen content in solid wastes will lead to higher reactivity during combustion, which means ignition of solid wastes at lower temperature followed by the fast release of volatiles during the thermal process.⁴² The heating value of RDF and coal is quite close to each other. Municipal solid waste heating value is lowest among the samples. Ultimate analysis of coal reveals that selected coal is low-rank coal with the highest content of sulfur among the selected samples. The potential for energy recovery from 5000 tons/d of MSW and RDF in Lahore (the 2nd largest city of the country) is presented in Table 4. This shows that the thermal decomposition of solid wastes will cause a considerable reduction in energy gap between supply and demand of Lahore.

TABLE 4 Potential for energy recovery from MSW and RDF in Lahore by incineration

Order	Material	Conversion efficiency (%)	LHV ^a (kJ kg ⁻¹)	Energy recoverable per ton of fuel (kW hrton ⁻¹)	Total energy recovered from (5000 ton/d) (MW)
1	MSW	25	8356	581	121
2	RDF	25	27 000	1117	232

^aAs received basis.**FIGURE 2** A, TG curves of coal, MSW and RDF samples at four heating rates. B, DTG curves of coal, MSW, and RDF at four heating rates

3.2 | Thermal decomposition analysis

Thermogravimetric (TG) and derivative of thermogravimetric (DTG) profiles clue us to the precise mapping of thermal processes for different fuels.⁴⁴ Usually, TG profile consists of three regions. In first region, physically and externally bound moisture is released. The second region is associated

with the release of low and high volatile organic matters, and the third region is about combustion of fixed carbon in the fuel. Figure 2A,B shows the TG and DTG profiles of three selected fuels at four heating rates (10, 20, 30, and 40 °C/min), respectively. The TG curves in Figure 2A showed that the weight loss in the first and third region was less prominent, as all samples were containing very low moisture and

TABLE 5 Temperature ranges for main regions at four heating rates during combustion

Sample	Temperature range (°C)												
	Heating rate	10°C/min			20°C/min			30°C/min			40°C/min		
		Region	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd
Coal		25-337	337-658	658-910	25-353	353-711	711-935	25-366	366-771	771-950	25-373	373-822	822-950
MSW		25-166	166-543	543-641	25-173	173-561	561-652	25-181	181-607	607-652	25-181	181-653	653-652
RDF		25-211	211-531	531-625	25-222	222-546	546-643	25-226	226-555	555-645	25-230	230-588	588-645

fixed carbon. Thermal decomposition of coal results in one major peak. This peak is associated with the release of carbon-containing volatile matter.⁴⁵ In the MSW DTG curves as shown in Figure 2B, two main exothermic peaks were noticed at 329°C and 474°C, while in RDF DTG curves, two main peaks were obtained at 367°C and 427°C. The existence of different shoulders/peaks may be attributed to the heterogeneous nature of solid wastes. For example, the presence of cellulose and hemicelluloses (relatively material of high reactivity) in MSW results in combustion at lower temperatures, while the presence of lignin (low reactivity material) may require higher temperature for its complete combustion.^{37,46,47} To further analyze, as MSW contains textile, nylon plastic bags, and PET bottles too, which present different peaks during the combustion process. When the combustion temperature and combustion speed of various types of volatile matters included in solid waste samples are close to each other, overlapping of temperature ranges may cause less number of peaks.^{22,48,49}

Apart from the heating rates, coal shows slow weight loss as compared to solid wastes (MSW and RDF). These solid wastes display high weight loss mainly between 180°C and 540°C due to their high activity, whereas coal weight lost is between 396°C and 630°C. The slow weight loss in coal may be due to high inert content (ash) and low volatile content. This makes the decomposition process to occur at higher temperature,^{50,51} as indicated in Figure 2A.

Combustion of fuel at various heating rates is an important parameter, regarding decomposition temperature ranges and kinetics. At different heating rates, exposure of fuel particles (residence time) varies, which changes the thermal degradation process. It is observed that with the increase in heating rate, the temperature ranges for start and endpoint increase due to thermal lag as shown in Table 5. This means increasing heating rate shifts the reaction zone to the higher temperatures for coal and solid wastes.^{22,39,48} The effect of heating rate on thermal decomposition of solid wastes and coal is presented in Figure 2B. The effect of increasing heating rate on reactivity was investigated at peak temperatures and VM/FC. In both cases, the order of reactivity found was MSW > RDF > coal. These peak temperatures at increasing heating rate demonstrate that with the increase in temperature, the reactivity increases. This variation may be explained on the basis of residence time. At low heating rate, fuel particles have more exposure and residence time, which leads to penetration of thermal gradient to the inner core of particles. At high heating rates, the residence time is less that eventually results in a nonuniform spread of thermal gradient into particles. Mean heat transfer is more efficient and effective at a lower temperature than high temperature. This is the main reason for wide temperature span at low temperature and narrow temperature span at high temperature as presented in Table 5.

TABLE 6 The combustion characteristic parameters for all samples at heating rate (10°C/min)

Samples	T_i (°C)	T_f (°C)	T_1 (°C)	T_2 (°C)	M_f (%)	DTG ₁ (mg/s)	DTG ₂ (mg/s)	DTG _{mean} (mg/s)
Coal	443	713	562	–	31.8	0.89	–	0.02
MSW	220	560	294	455	10.2	0.07	0.11	0.05
RDF	236	554	341	465	9.3	0.14	0.12	0.06

Note: T_i : the ignition temperature, T_f : burnout temperature, T_1, T_2 : temperature at maximum weight loss rate of first peak and second peak, M_f : the combustion residue mass, DTG₁, DTG₂: the mass loss rate for first peak and second peak.

For thermal behavior and characterization studies, ignition and burnout temperatures were obtained from TG and DTG profiles of samples at a heating rate of 10°C/min. as shown in Table 6. Among the tested solid samples, coal has the highest ignition temperature (443°C), while MSW and RDF have very close ignition temperature values of 220°C and 236°C, respectively. Although MSW has low volatile content compared to that of RDF, still combustion of MSW starts slight earlier to RDF. This probably can be due to the presence of volatile matters, which includes a lot of organic matter content from biodegradables in MSW.⁴⁸ The burnout temperature of coal (713°C) is higher than the MSW (560°C) and RDF (554°C), and this is due to higher ash content, which further characterizes the burnout process. The combustion residue mass percentage of coal, MSW, and RDF are 31.8%, 10.2%, and 9.3%, respectively. Compared to MSW and RDF, more noncombustible matter is obtained in case of coal. This means that the addition of MSW and RDF in the coal combustion process may improve the combustion characteristics of coal. The DTG_{mean} values of selected fuels are found to be in the descending order of RDF, MSW, and coal. This implies that solid wastes will burn out faster than coal.

3.3 | Kinetic analysis

As mentioned above, the thermal decomposition of coal and solid wastes mainly took place in the second stage of the overall process, so for kinetic analysis, peaks with maximum weight loss in the second stage are mainly taken into concern. Two model-fitting models, Arrhenius and Coats-Redfern, were used to compare the applicability of models for solid fuel combustion process. Two key stages of applying model-fitted methods are as follows: (a) selection of the model that best fits the data and (b) determination of the kinetic parameters such as the activation energy and R^2 .⁵² In Arrhenius model, the plot of $\ln[da/dT/(1 - \alpha)^n]$ vs $1/T$ resulted in lines for different values of n . In the case of Coats-Redfern model, the plot of the left-hand side of Equation (9) vs $1/T$ leads to approximately straight lines for each reaction mechanism listed in Table 3. For estimation of activation energy from these models, the slope of the line having the best fit to experimental data was considered.

The estimated results of activation energy from both models at different heating rates and reaction mechanism

are listed in Tables 7 and 8. Arrhenius model assessed that the solid waste conversion took place by third-order reaction mechanism (D3), while coal conversion took place by power law (P2) reaction mechanism. The Coats-Redfern model estimated that coal conversion followed mainly second-order diffusion conversion reaction mechanism (D2), whereas MSW and RDF conversion followed different reaction mechanisms as shown in Table 8. The activation energies of the combustion process from the Arrhenius model are distributed in between 91 and 124, 53 and 68, and 40 and 107 kJ/mol for coal, MSW, and RDF respectively, while the Coats-Redfern model displays activation energies of the combustion process in between 106 and 162, 35 and 85, and 36 and 116 kJ/mol for coal, MSW, and RDF, respectively. According to the kinetic analysis result of these models, the selected fuels may be arranged in order of activation energy as coal > RDF > MSW.

In case of coal, the comparison of obtained activation energies showed that both models provided closer results, followed by the display of the high value of R^2 . In the case of solid wastes, the values of obtained activation energies for MSW and RDF display a larger range of percentage difference (4.1-26.5). This may be due to the heterogeneous nature of solid wastes. The results are sensitive to solid waste characteristic, experimental condition, and kinetic method used. Therefore, one should compare the values of activation energy when using the same kinetic method.⁵³ Comparison of obtained activation energies and values of R^2 showed that the Coats-Redfern model has displayed better results at different heating rates. There is an ongoing debate about the accuracy and reliability of model-fitted methods. Model-fitted methods had preassumption of reaction mechanism, which inculcates inherent inaccuracy and leads to a wrong understanding of the combustion process. Some researchers have pointed out that even model-fitting methods can predict satisfactory reaction kinetic results for solid fuels. However, the application of the model may not able to describe involved simultaneous complex reaction during the decomposition process.⁵⁴

4 | CONCLUSION

In this research, combustion characteristics and kinetic parameters of solid fuels such as coal, MSW, and RDF were investigated using thermogravimetry (TG-DTG) at different

TABLE 7 Calculated E (kJ/mol) and R^2 values, obtained from Arrhenius model

Coal	MSW—1st peak			MSW—2nd peak			RDF—1st peak			RDF—2nd peak								
	β (°C/min)	n	E (kJ/mol)	β (°C/min)	n	E (kJ/mol)	β (°C/min)	n	E (kJ/mol)	β (°C/min)	n	E (kJ/mol)						
10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40			
$n = 1.5$	$n = 1.5$	$n = 1.5$	$n = 1.5$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$	$n = 3$			
124	114	97.9	91.3	67.1	62.2	59.7	56.6	60.3	57.2	55.8	53.1	106.1	98.4	94.3	91.3	43.2	41.9	39.7
R^2	0.98	0.94	0.94	0.95	0.95	0.94	0.84	0.83	0.93	0.92	0.55	0.89	0.95	0.96	0.96	0.88	0.95	0.83

TABLE 8 Calculated E (kJ/mol) and R^2 values, obtained from Coats-Redfern model

Coal	MSW—1st peak			MSW—2nd peak			RDF—1st peak			RDF—2nd peak										
	β (°C/min)	n	E (kJ/mol)	β (°C/min)	n	E (kJ/mol)	β (°C/min)	n	E (kJ/mol)	β (°C/min)	n	E (kJ/mol)								
10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40					
D3	D2	D2	D2	D1	$n = 3$	$n = 2$	D4	2-D	D3	D3	D4	D4	D4	$n = 0.5$	$n = 0.5$	$n = 0.5$				
162	125	115.1	105.1	84.1	80.6	78.3	78.5	53.8	51.9	43.8	34.2	116.7	116.2	115.6	115.5	47.2	41.4	40.2	36.2	
R^2	0.98	0.97	0.97	0.98	0.93	0.98	0.98	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.99	0.94	0.95	0.97	0.98	
% Difference ^a	26.5	9.2	16.2	13.9	22.4	25.7	27	32	11.4	9.7	24.1	20.5	9.6	16.5	20.3	23.4	4.1	4.2	4.1	9.2

^a% Difference = $(V_1 - V_2) \times 200 / (V_1 + V_2)$.

heating rates. Further, proximate and ultimate analyses were carried out along with their heating values. The following outputs were derived from this research work.

- Solid wastes contain high volatile content and low fixed carbon, whereas coal contains high ash and sulfur contents. It was worth noting that the heating value of RDF was closer to coal.
- According to TG and DTG curves of selected fuel samples, it was observed that MSW and RDF involved two-stage combustion, which mainly consists of decomposition of cellulose and plastic structure compared to single-stage coal combustion. The rate of decomposition, ignition, and burnout temperature of all solid fuels increased with increase in heating rate.
- The reactivity of samples during the combustion process was in the order of MSW > RDF > coal. It means higher reactivity of solid wastes can positively support the combustion of low-quality Pakistani coal, due to their ability to lower the ignition temperature. Further, it can facilitate the reduction of SO₂ emission during combustion of coal due to the low sulfur content of solid wastes.
- The Coats-Redfern model showed consistency in obtained activation energy values and high value of R^2 at different heating rates, with a percentage difference range of 4.1%-26.5% compared to the Arrhenius model.

This study recommends that the combustion and cocombustion of solid wastes (MSW and RDF) with coal could be a promising alternative renewable energy source, resulting in better waste management strategies, including a reduction in GHG emission.

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NOMENCLATURE

TGA	thermogravimetric analysis
MC	moisture content
FC	fixed carbon
RDF	refuse-derived fuel
HHV	high heating value
VM	volatile matter
MSW	municipal solid waste
ad	air-dried basis
daf	dried ash-free basis
α	fractional conversion

E	activation energy (kJ/mol)
A	preexponential factor
β	heating rate (°C/min)
R	general gas constant
$f(\alpha)$	differential form of reaction model
$g(\alpha)$	integral form of reaction model
R^2	correlation coefficient
n	order of reaction

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