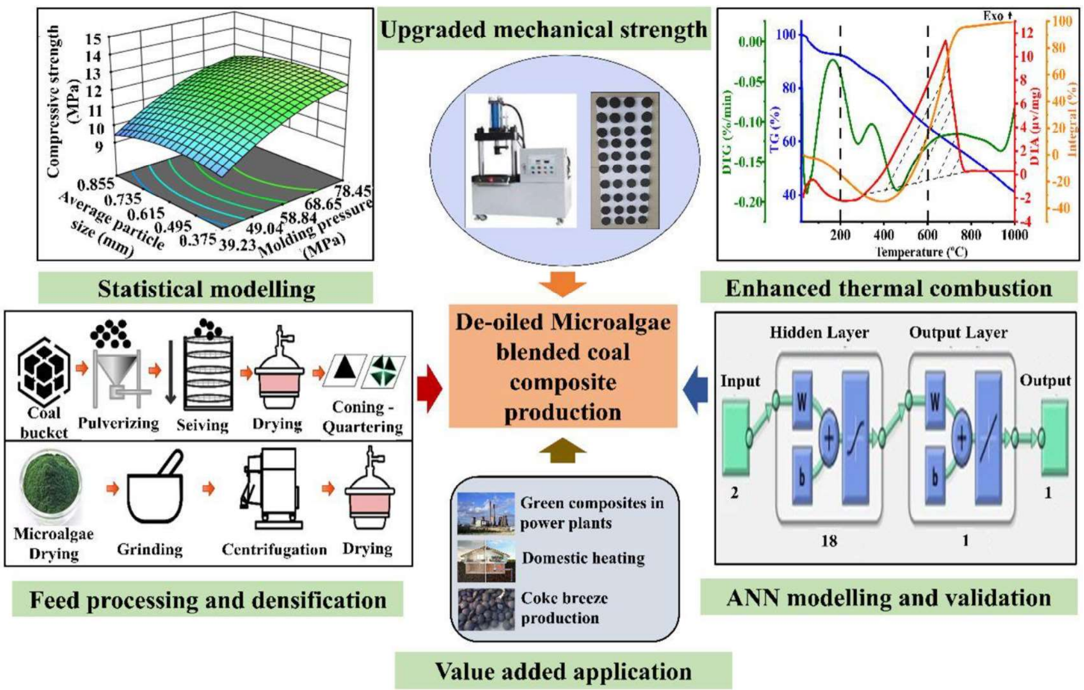
CHAPTER 5

Co-investigation of mechanical performance and thermal behavior of de-oiled microalgae blended coal composites*



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Abstract

Present chapter investigates utilization of de-oiled microalgae, *C. pyrenoidosa* NCIM2738, as a binder to densify low-rank coal waste to formulate upgraded biomass-blended coal composites. The de-oiled biomass has shown a similar gross calorific value (18.62 MJ/kg), sulfur content (1.45%), and low ash content (18%) in comparison to coal. Fuel characteristics of biomass-blended coal composites of 20:80 ratio showed gross calorific value (19.0 MJ/kg), fuel ratio (1.85), and low sulfur content (< 1%). The multi-objective optimization strategy is used to optimize the molding pressure, average particle size, and binder ratio to maximize the mechanical performance indicators such as compressive strength and drop strength of biomass-blended coal composites. The maximum compressive strength and drop strength of blended composites at multi-objective optimized conditions after model validation (R^2 > 0.99) are observed to be 14.6 MPa and 97.8%, respectively. Fourier transform infrared analysis is used to evaluate structural variation during coal-microalgae interaction. Thermogravimetric analysis, derivative thermogravimetric, and differential thermal analysis (TGA-DTG-DTA) are conducted to determine characteristic temperature points and heat involvement during combustion. TGA-DTG-DTA showed remarkable shifting of ignition point from 335 °C (parent coal) to 301–299 °C (blended coal composites), extended burnout temperature (47–82 °C higher than parent coal), and excessive exothermic heat involvement (3305–3363 μVs/mg) during composite combustion. Levenberg-Marquardt algorithm–based artificial neural network model is applied to validate the thermal analysis of coal, microalgae, and blended composites, which offers an excellent tool for studying thermochemical conversions. An in-depth investigation of mechanical-thermal aspect of the coal-biomass energy system will provide new possibilities to select microalgae as binder with optimized binder ratios which can apply in coal-based power plants as sustainable and affordable fuels.

5.1 Background

This chapter focuses on blended solid fuel processing technologies to utilize de-oiled microalgae, *C. pyrenoidosa* NCIM2738, as a binder to densify low rank coal waste and formulate upgraded biomass-blended coal composites. Densification of algal biomass with coal is one of the best approaches due to the compatible physical properties of both materials, such as moisture content, particle size distribution, and bulk density (Thapa et al., 2015). In addition, algal-blended solid fuels offer improved mechanical performance in the form of compressive strength, drop strength, and water resistance index (WRI) (Nyoni et al., 2020; Cui et al., 2019). Compared to pure coal, the combustion of microalgae blended coal pellets significantly reduces the emission of carbon dioxide, sulfur, and nitrogen oxides (Nyoni et al., 2020). In a similar aspect, the blending ratio range of *Scenedesmus* (5–20%) to coal reports the reduction of CO_2 (12–29%) and SO_2 emissions (3–19%) during the combustion process (Magida et al., 2022). These studies indicated that sustainable utilization of waste coal might be possible through microalgae-blended briquettes with minimum adverse environmental impact. However, blending biomass in coal more than 10% is not recommended. It is considered a limitation in coal-based boilers due to the possibility of fire hazards at low ignition, feeding issues, and the opposite impact on thermal combustion (Kwong et al., 2007).

In this direction, the present chapter investigates de-oiled microalgae *C. pyrenoidosa* NCIM2738 as a novel binder to blend with waste coal residues to target coal replacement with biomass and minimal impact on fuel quality. The main content of chapter includes selection/pre-processing of selected fuel feedstock and fuel characterization using proximate and ultimate analysis. Further, individual and multi-objective optimization was performed to formulate microalgae-blended coal composites (MBCCs) of high compressive and drop strength. TGA-DTG-DTA were conducted to evaluate thermal properties of MBCCs. Levenberg-Marquardt (LM) algorithm–based artificial neural network (ANN) model was applied to validate the thermal analysis of coal, microalgae, and blended composites. Thermal decomposition of blended fuels through ANN approaches provides quick predictions of the most complex thermal analysis without undergoing rigorous estimations (Rasool et al., 2021).

This chapter primarily focuses on utilization of low rank coal residues by blending with de-oiled microalgae. After bio-oil extraction from microalgae, de-oiled biomass can be further utilized to produce composites that enhance energy recovery and minimize waste. The de-oiled microalgae biomass blending with coal fines effectively enhances energy yield and economic viability and captures carbon in commercial combustion (Muazu et al., 2017). Blending de-oiled microalgae biomass with coal as composites shows better calorific value, high fuel ratio, less ash content, and suitable combustion characteristics than woody biomass and agriculture residue (Chen et al., 2012). The application domain of such pellets is limited for coal-enriched developing countries that need a low-cost and easily usable type of solid fuel to fulfill energy demands.

The co-investigation of mechanical performance and thermal behavior of microalgae-blended solid fuel will develop a basic framework for large-scale production. The present investigation provides fundamental operational guidance for critical aspects such as appropriate biomass selection as coal binder, optimized blending ratio determination, adverse impact assessment of moisture content, ash content, and particle size upon boiler combustion efficiency and overall performance. Higher proximity of ANN predictions in thermochemical conversion encourages modeling for pyrolysis scale-up, thermal property estimation and designing of biomass responsive boilers for large-scale commercial production.

5.2 Materials and methods

5.2.1 Sampling, processing, and basic fuel characterization of raw sample

The waste coal fines were collected from Amelia coal mine block, Seam VII, main basin, Singrauli coalfield, India (location, latitude 2405′2.56″ N, longitude 82026′11.86″ E). The unsuitability of raw coal fines as fuel leads to coal preprocessing, including sample preparation, screening, pulverization, sieving (sieve size 8–80), and coning-quartering by following the standards of the ASTM. The low rank coal excavation from Amelia coal block is shown in Fig. 5.1. The particle size distribution data of pulverized coal is shown in Table 5.1.

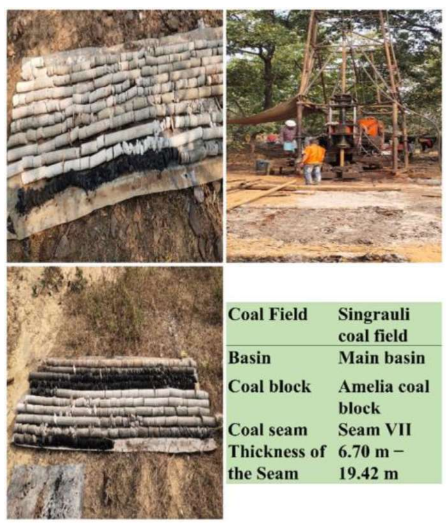

Fig. 5.1 Low rank coal excavation from Amelia coal block.

Table 5.1 Particle size distribution of the investigated low rank coal sample.

Sieve (Mesh in ASTM)	Average particle size (mm)	Weight (g)	Mass yield (%)
8	> 2.38	15.26	0.62
12	2.03	150.5	6.11
18	1.34	205.12	8.33
25	0.855	250.54	10.18
35	0.615	575	23.36
60	0.375	590	23.97
80	< 0.250	675	27.42

Microalgae (*C. pyrenoidosa*) was utilized as a binder for coal-biomass blending. In this regard, *C. pyrenoidosa* (NCIM 2738) was cultivated in CME (explained in the previous section). After harvesting, lipid was extracted from algal powder using Bligh and Dyer's method as described by Pandey et al. (2019). The residual de-oiled microalgae was washed twice to remove excess salt content from biomass. After drying and grinding, de-oiled algae powder was stored in a desiccator for coal densification. The schematic representation of MBCCs production is shown in Fig. 5.2.

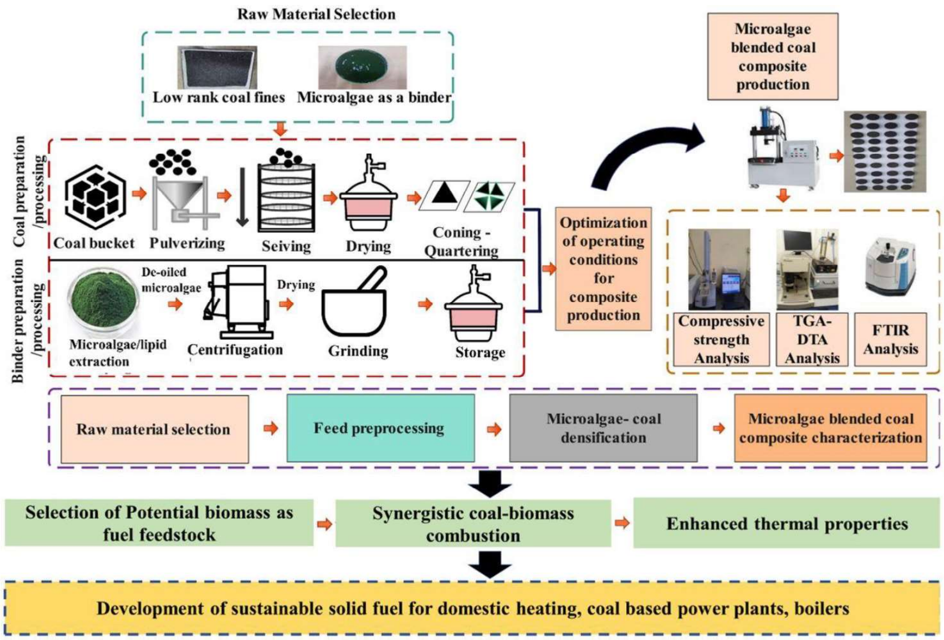

Fig. 5.2 Schematic representation of microalgae blended coal composite (MBCC) production.

5.2.2 Microalgae-blended coal composite preparation and characterization

Microalgae and coal fines were densified in pellets to produce upgraded solid fuel, which can be further utilized for domestic and industrial purposes. In this regard, dried and pulverized coal samples of different particle sizes were blended with processed algae, *C. pyrenoidosa* as natural binder in different ratios (80:20, 85:15, and 90:10). Ten-gram mixture of coal fines and microalgae powder was mixed with 2 mL of water for one h before briquette production (Gendek et al., 2018). The standard briquette manufacturing method was used to prepare blended solid fuels by adding water for moisture, facilitating better adhesion (intermolecular bonding) between solid particles (Gendek et al., 2018; Guo et al., 2020). A hydraulic pellet press (Insmart Systems, Hyderabad, India) was used to pelletize coal-microalgae-blended material. The blended mixture was placed in a die-set chamber for each experiment. The die-set was moved by applying compression upon the sample using the plunger of the pellet press. According to the experimental design, molding pressure of 39.2 MPa, 58.8 MPa, and 78.5 MPa was applied to the material for constant time (60 s) for pelletization. After this holding period, the molding pressure was automatically released and the prepared coal microalgae pellets were removed from the machine. The proximate analysis of coal, de-oiled microalgae biomass, and MBCCs was analyzed according to ASTM D7582-15 standard. The ultimate analysis of all studied materials was analyzed using CHN628 elemental analyzer (LECO, Michigan, USA) according to ASTM D5373-14 standard. Gross calorific value (GCV) was determined by Parr 6100 oxygen bomb calorimeter (Parr Instrument, USA) using ASTM D5865-13 for all samples (Zhang et al., 2020).

5.2.3 Mechanical, thermal and Fourier transform infrared analysis of composites

Mechanical and thermal properties are vital parameters that indicate the quality of any solid fuel. The mechanical durability of pellets was tested for compressive strength, drop strength, and WRI. The compressive strength of prepared MBCCs was determined through a texture analyzer (EZ-SX, Shimadzu, Kyoto, Japan) with 500-N bearing capacity and applied compression at 20% sample thickness as per the given Eq. 5.1.

$$\mathrm{CS} = \frac{4\mathrm{M_F}}{\pi \mathrm{D}^2} \tag{5.1}$$

CS is compressive strength, MF is the maximum applied load before breaking, and D is the pellet's circular diameter. Further, drop strength and WRI were analyzed according to coal industry standard GB/T15459-2006 and modified Richard's method, respectively (Guo et al., 2020; Fermoso et al., 2018).

The spectra of raw coal, microalgae, and MBCCs were recorded by Cary 630 FTIR (Agilent, California, USA) using a KBr pellet in the 500– 4000 cm^{-1}. Combustion characteristics of studied samples were investigated using a TGA-50 thermogravimetric analyzer (Shimadzu, Kyoto, Japan) in a temperature range of 21–1000 °C at a heating rate of 10 °C/ min and a nitrogen flow rate of 100 mL/min.

5.2.4 Statistical modeling and analysis

For good-quality pelletization, statistical RSM modeling was applied to identify the optimum conditions of significant process variables (molding pressure, coal particle size, and binder ratio). Compressive and drop strength were considered output quality parameters for individual and multi-objective optimization of prepared pellets. Design-Expert®, software version 13, Stat-Ease, USA, was used for Box-Behnken experiments design and analysis as described by Pandey et al. (2019). Compressive strength (Y_1) and dropping strength (Y_2) of the MBCCs were investigated under varied molding pressure, X_1 (39.2 – 78.5 MPa), average coal particle size, X_2 (0.375 – 0.855 mm), and binder ratio, X_3 (10 – 20%) as presented in Table 5.2.

Table 5.2 Factors and levels of microalgae-blended coal composites (MBCCs) production.

Level	Factors		
	Molding pressure (MPa), X_1	**Average coal particle size(mm), X_2**	**Binder ratio (%), X_3**
-1	39.2	0.375	10
0	58.8	0.615	15
1	78.5	0.855	20

5.2.5 Uncertainty analysis

Uncertainty analysis is very significant in quantifying the variability of the output parameters (compressive strength and drop strength) due to variability in the input parameters (molding pressure, average particle size, and binder ratio). To increase the credibility of the results, the Monte-Carlo simulation was conducted using IBM SPSS statistics 29.0. Monte Carlo simulation allows flexible evaluation of uncertainty on the output variables by using complex and multiple correlations of the input variable by repeated and random sampling of parameters (Dadamos et al., 2019). The Monte Carlo simulation was applied to determine the uncertainty of mechanical performance indicators, compressive strength, and drop strength with a 99% confidence interval by referring to reported literature (Song et al., 2020). The simulation was performed 50,000 times with random data selection within a feasible range using statistical analysis of the output results.

5.2.6 Artificial neural network simulation

The thermal analysis data of coal, microalgae, and composites were validated using the ANN model simulated by MATLAB®R2022b. The shallow multilayer (2 layers) feedforward neural network was used to train, validate, and test the experimental data. The architecture of ANN was designed with two input layers, temperature (°C) and heating rate (°C/min), obtained from the experimental data, and the residual mass (wt%) as the output. One hidden layer involving tan-sigmoid (18 neurons) and an output layer involving pure linear (purelin) transfer function were used to predict the outcome. The model was trained with the Levenberg–Marquardt algorithm using the dividerand function to divide the data among training, validation, and test sets in a 70-15-15 ratio (Rasool et al., 2021).

5.3. Results and discussion

5.3.1 Impact of pelleting material on fuel characteristics of composites

Fuel characteristics analysis such as proximate, ultimate, and GCV are preliminary and essential to determine feedstock quality for pelletization. Proximate analysis indicates fixed carbon, moisture content, ash content, and volatile matter in the analyzed sample. Examining the ash and moisture content of coal and microalgae is crucial due to their adverse impact on the boiler's efficiency. The composition of raw materials (coal and biomass) directly affects the composition and properties of blended solid fuel. In this regard, ultimate analysis is a convenient approach to determine the elemental composition (mass % of C, H, N, S) of fuel feedstock. The hydrogen/carbon ratio and oxygen/ carbon ratio are essential parameters for fuel combustion efficiency. Further, the GCV content of fuel directly corresponds to fuel quality.

The de-oiled microalgae biomass was used as a binder to densify coal fines in composites. The proximate, ultimate, and GCV analysis results of raw materials (coal and de-oiled microalgae biomass) and their blended composite defined as 20% binder: 80% coal are presented in Table 5.3. The low rank parent coal showed high moisture content (7.90%), high ash residues (40.0%), and average GCV (19.24 MJ/kg), which is consistent with other reported literature (Guo et al., 2020). In comparison, GCV and ash content of de-oiled microalgae biomass were 18.62 MJ/kg and 18%, respectively. This composite fuel based on microalgae and coal fines may lead to improved combustion behavior and better interaction. The GCV content, fixed carbon, and fuel ratio of MBCCs lay between coal and microalgae, with ash reduction from 40% (raw coal) to 33.5% (composite fuel). These results indicate that the fuel properties of both raw materials (coal and de-oiled microalgae biomass) are compatible with producing a blended composite with an adequate fuel ratio of 1.85 (Table 5.3).

Table 5.3 Basic fuel characteristics of investigated waste coal, microalgae, and microalgae blended coal composites (MBCCs).

	Proximate analysis (mass %)		Ultimate analysis (mass %)
Raw coal			
Moisture	7.90	C	58.86
Volatile matter	13.50 (low volatile steam coal)[a]	H	4.53
Fixed carbon	38.60	O	34.11
Ash	40.0 (very low-quality ashy coal)[a]	N	<1.00
Mineral matter	44.0[b]	S	<1.00
Pyrite	<1.00[c]	C/H	13
Fuel ratio	2.86[d]	O/C	0.58
GCV(MJ/kg)	19.24		
De-oiled microalgae biomass (*C. pyrenoidosa*)			
Moisture	4.94	C	45.06
Volatile matter	43.01	H	6.62
Fixed carbon	34.05	O	41.20
Ash	18.0	N	5.67
Mineral matter	19.8	S	1.45
Pyrite	8.30	C/H	6.81
Fuel ratio	0.79	O/C	0.91
GCV (MJ/kg)	18.62		
Microalgae blended coal composite (20%:80%)			
Moisture	9.50	C	56.09
Volatile matter	20.0	H	5.01
Fixed carbon	37.0	O	36.70
Ash	33.50	N	1.21
Mineral matter	36.85[b]	S	<1.00
Pyrite	<1.00[c]	C/H	11.2
Fuel ratio	1.85[d]	O/C	0.65
GCV(MJ/kg)	19.00		

All-observed values of responses are mean values of duplicates and standard deviation less than 3%. [a]Classification based on Jankovic et al. (2020); [b]mineral matter mass % = 1.10. (ash mass %) (Krishnaiah et al., 2012); [c]pyrite = 130. (S mass% − 0.30)/ Ash mass % (Krishnaiah et al., 2012); [d]Fuel ratio = Fixed carbon / Volatile matter (Jankovic et al., 2020); GCV: Gross calorific value.

5.3.2 Optimization of process variables to maximize the mechanical performance of microalgae blended coal pellets

The mechanical strength of prepared pellets, such as durability, density, compressive strength, and drop strength, depends on the process variables (molding pressure, binder ratio, and particle size) during pelletization. As a significant process variable, molding pressure directly affects the mechanical compactness of composites (Adeleke et al., 2021). The binder ratio also influences the mechanical strength of blended pellets as it strengthens the binding of coal particles through intermolecular bond formation. In this direction, Buravchuk and Gur'yanova (2018), Kan et al. (2016), and Manyuchi et al. (2018) have reported binder ratios in the range of 6–10% molasses, 10% cassava starch, and 8% molasses, respectively, for co-densification studies. A higher molding pressure (≥ 23–25 MPa) and binder ratio (≥ 10%) are recommended for enhanced strength and durable briquette preparation (Guo et al., 2020). Opposite to molding pressure and binder ratio, particle size adversely affects the mechanical properties of composites. Coal powder with an average particle size of less than 1 mm provides better binding results (due to sufficient contact area) for densification (Popov et al., 2018). Based on the above considerations, the range of process variables was selected for microalgae-blended coal pellet production (Table 5.2).

The statistical approaches (RSM) provide a convenient tool to maximize the product quality, such as compressive and drop strength, by optimizing process variables, defined as molding pressure, average particle size, and binder ratio. In this direction, 15 experiments with three center points were performed according to Box-Behnken design (Table 5.4).

Table 5.4 Box- Behnken design matrix and results for microalgae blended coal composites (MBCCs) production.

Run	Molding pressure (MPa), X_1	Average coal particle size (mm), X_2	Binder ratio (%), X_3	Compressive strength, (MPa), Y_1	Drop strength, (%), Y_2
1	58.8 (0)	0.615 (0)	15 (0)	12.0±0.1	90.85±0.23
2	58.8 (0)	0.615 (0)	15 (0)	12.1±0.3	92.10±0.35
3	58.8 (0)	0.615 (0)	15 (0)	12.0±0.2	92.10±0.17
4	39.2 (-1)	0.375(-1)	15(0)	9.6±0.2	61.42±0.51
5	39.2 (-1)	0.855(1)	15 (0)	9.6±0.3	46.11±0.55
6	39.2 (-1)	0.615 (0)	10 (-1)	9.2±0.1	46.10±0.16
7	39.2 (-1)	0.615 (0)	20 (1)	11.1±0.9	67.15±0.51
8	58.8 (0)	0.855 (1)	20 (1)	12.6±0.1	93.01±0.08
9	58.8 (0)	0.375 (-1)	20 (1)	13.5±0.3	97.75±0.42

Run	Molding pressure (MPa), X_1	Average coal particle size (mm), X_2	Binder ratio (%), X_3	Compressive strength, (MPa), Y_1	Drop strength, (%), Y_2
10	58.8 (0)	0.855 (1)	10 (-1)	9.9±0.4	82.50±0.29
11	58.8 (0)	0.375 (-1)	10 (-1)	10.3±0.4	88.10±0.31
12	78.5 (1)	0.615 (0)	20 (1)	14.7±0.2	95.10±0.17
13	78.5 (1)	0.375 (-1)	15 (0)	12.4±0.2	91.50±0.52
14	78.5 (1)	0.855 (1)	15 (0)	12.5±0.4	91.82±0.27
15	78.5 (1)	0.615 (0)	10 (-1)	10.9±0.1	91.84±0.24

Y_1 and Y_2 are the mean values of duplicates with standard deviation (mean ±SD).

Further, MBCCs were prepared for different conditions and examined for dimension, mass, and bulk density. These composites have a uniform cylindrical shape with dimensions of 4 × 0.7 cm. The mean mass of each composite was measured as 9.45 ± 0.34 g, with average mass loss lying in the range of 0.38 to 0.54 g/g. The mean bulk density of pellets was obtained as 1100 kg/m^3. These pellets were further analyzed for mechanical performance in the form of compressive strength and drop strength. Experimental results showed a significant variation in compressive strength from 9.2 to 14.7 MPa and drop strength from 46.10 to 97.75% (Table 5.4).

The uncertainty of defined factors, such as molding pressure, average particle size, and binder ratio, influencing the mechanical strength of pellets (compressive strength and drop strength), were analyzed by Monte Carlo simulation (Table 5.5). In the case of compressive strength, the calculated uncertainty coefficient for molding pressure and binder ratio was observed minimum (0.097). Conversely, uncertainty was more significant for targeting particle size as a variable responding to compressive strength (0.525). However, all three variables (molding pressure, particle size, and binder ratio) showed equal uncertainty (0.317) for drop strength. The positive Spearman's rank-order correlation for molding pressure (0.656) and binder ratio (0.699) indicated both variables, molding pressure and binder ratio, synergistically contribute to increasing compressive strength. Similar results can be seen in the case of drop strength.

Table 5.5 Uncertainty estimation of each parameter by Monte Carlo simulation.

Compressive strength			Drop strength		
Variables	**Uncertainty coefficient[a]**	**Rank correlation[b]**	**Variables**	**Uncertainty coefficient**	**Rank correlation**
Molding pressure	0.097	0.656	Molding pressure	0.317	0.656
Average particle size	0.525	-0.021	Average particle size	0.317	-0.063
Binder ratio	0.097	0.699	Binder ratio	0.317	0.508

[a] Monte Carlo significance at 99% confidence interval; [b]Spearman's rho estimation.

Oppositely, the negative correlation of particle size was observed for compressive strength (− 0.021) as well as drop strength (− 0.063), which is also supported by literature stating that reduced particle size of material shows better binding strength (Rawat and Kumar (2021).

5.3.3 Pelletizing process variables optimization to maximize the individual response

The pelletizing process variables (molding pressure, binder ratio, and particle size) directly impact the mechanical strength (compressive and drop strength) of pellets. Quadratic polynomial equations were established via regression coefficients calculation for the compressive and drop strength (Table 5.6). Multiple regression analysis in experimental data was performed to determine the relationship between process variables and measured responses (Table 5.7). Multiple regression analysis equations indicated the high significance of all linear and quadratic terms of process variables based on p-value ($p < 0.05$) (Table 5.7). The interaction of molding pressure with binder ratio and average particle size was significant for drop strength ($p < 0.001$). Similarly, the interaction of molding pressure with the binder ratio was also significant for compressive strength (p-value = 0.001). The R^2 for compressive strength and drop strength were 96.89% and 99.81%, respectively, indicating an excellent fitting effect of both models.

The analysis of variance results was summarized after analyzing all measured experimental responses (Table 5.8). The quadratic regression models were highly significant, as the F values of compressive strength and drop strength were 69.19 and 1166.40, respectively, with the corresponding p values < 0.001. The linear, square, and interaction of all model terms were significant for compressive strength and drop strength ($p < 0.05$) with the varying impact of variables in order of molding pressure > binder ratio > average particle size.

Table 5.6 Quadratic polynomial equations for the compressive and drop strength of microalgae blended coal composites (MBCCs) production.

Coded term:	
Y_1 =	$12.03 + 1.41 X_1 - 0.15 X_2 + 1.45 X_3 - 0.55 X_1^2 - 0.47 X_2^2 + 0.003 X_3^2 + 0.02X_1X_2 + 0.45X_1X_3 - 0.16 X_2X_3$
Y_2 =	$91.71 + 18.69 X_1 - 3.17 X_2 + 5.56 X_3 + 17.15 X_1^2 - 1.85 X_2^2 + 0.48 X_3^2 + 3.91X_1X_2 - 4.45 X_1 X_3 + 0.22 X_2 X_3$
Uncoded term:	
Y_1 =	$-1.19 + 0.169 X_1 + 11.15 X_2 + 0.096 X_3 – 0.001 X_1^2 – 8.15 X_2^2 + 0.0001 X_3^2 + 0.004 X_1 X_2 + 0.004 X_1 X_3 – 0.133 X_2 X_3$
Y_2 =	$- 143.40 + 6.368 X_1 – 25.15 X_2 + 3.092 X_3 – 0.044 X_1^2 – 32.18 X_2^2 + 0.0193 X_3^2 + 0.8302 X_1 X_2 – 0.045 X_1 X_3 + 0.179 X_2 X_3$

X_1 : molding pressure; X_2 : average coal particle size; X_3 : binder ratio.

Table 5.7 Model coefficient estimate by multiple regression analysis for compressive strength and drop strength of microalgae blended coal composites (MBCCs) production.

Model term	**Compressive strength (MPa)**				**Drop strength (%)**			
	Coeff.	**SE**	**t value**	**p value**	**Coeff.**	**SE**	**t value**	**p value**
Constant	12.03	0.140	87.10	< 0.001	91.71	0.37	246.48	< 0.001
X_1	1.41	0.085	16.71	< 0.001	18.69	0.23	82.01	< 0.001
X_2	-0.15	0.085	-1.77	0.090	-3.17	0.23	-13.90	< 0.001
X_3	1.45	0.085	17.10	< 0.001	5.56	0.23	24.40	< 0.001
X_1^2	-0.55	0.130	-4.43	< 0.001	17.15	0.34	-51.12	< 0.001
X_2^2	-0.47	0.130	-3.77	0.001	-1.85	0.34	-5.53	< 0.001
X_3^2	0.003	0.130	0.02	0.980	0.48	0.34	1.44	0.170
X_1X_2	0.02	0.120	0.17	0.870	3.91	0.32	12.13	< 0.001
X_1X_3	0.45	0.120	3.78	0.001	-4.45	0.32	-13.80	< 0.001
X_2X_3	-0.16	0.120	-1.34	0.190	0.22	0.32	0.67	0.510

X_1: Molding pressure; X_2 : Average coal particle size; X_3 : Binder ratio; Coeff: coefficient; SE: Standard error; Compressive strength model: R^2= 96.89%; Drop strength model: R^2= 99.81%.

Table 5.8 Analysis of variance for different responses (compressive strength and drop strength).

Source	df	Compressive strength				Drop strength			
		SS	MS	F value	p value	SS	MS	F value	p value
Model	9	71.30	7.92	69.19	< 0.001	8719.92	968.88	1166.40	< 0.001
Linear	3	65.81	21.94	191.58	< 0.001	6240.87	2080.29	2504.38	< 0.001
Square	3	3.65	1.22	10.62	< 0.001	2198.29	732.76	882.15	< 0.001
Interaction	3	1.85	0.62	5.37	0.007	280.76	93.59	112.67	< 0.001
Residual error	20	2.29	0.11			20	16.61	0.83	
Lack-of-fit	3	0.49	0.16	1.53	0.243	10.81	3.60	10.57	0.087
Pure error	17	1.80	0.17			5.80	0.34		
Total	29	73.59				8736.53			

df : degree of freedom; SS : sum of squares; MS : mean square.

The three-dimensional surface diagrams revealed the interactive effects of process variables in the X-Y axis against the desired response on the Z axis by fixing the remaining variable at the center level for each plot (Fig. 5.3a–f). Increasing molding pressure (39.23–78.45 MPa), and decreasing particle size (0.855–0.375mm) indicated a sharp uptrend in both responses (compressive strength and drop strength) as shown in (Fig. 5.3a and d). The findings of Zhang et al. (2020) also confirm molding pressure's positive influence on compressive strength.

Similarly, binder ratio and molding pressure positively impact compressive strength and drop strength with the significance of $p = 0.001$ and < 0.001, respectively (Fig. 5.3b and e). In the direction of microalgae-based binder, Muazu and Stegemann (2015) reported that increasing the binder ratio affects the compressive strength and drop strength of briquettes positively as protein and lignin content of biomass binder (algae residues) forms a solid bridge and fills the voids between loose coal particles and strengthen coal bricks. Further, studies are reported in the literature to show the favorable impact of the lignin content of biomass to enhance the mechanical strength of pellets (Ververis et al., 2007). The interactive effect of binder ratio (10–20%) and reducing particle size (0.855–0.375 mm) showed less statistical significance for compressive strength and drop strength (p value = 0.19 and 0.51 respectively) (Fig. 5.3c and f). The flat curve of Fig. 5.3f represents composites prepared at mid value molding pressure (58.84 MPa) that are not influenced by binder ratio and average particle size. In the direction of blended solid fuels, Guo et al. (2020) reported molding pressure and binder ratio as the most significant parameters to influence the falling strength or drop strength of briquettes. Adeleke et al. (2021) reported that pitch-molasses-blended briquettes showed bulk density in the range of 1180–1320 kg/m^3, WRI 99%, and crushing strength 9 MPa.

Molding pressure, binder ratio and average particle size to maximize compressive strength and drop strength showed optimal desirability (>0.99). The maximum compressive strength for individual optimization was determined as 14.8 MPa at optimized process variables (78.5MPa molding pressure, 20% binder ratio and 0.539 mm average particle size) as represented in Fig. 5.4a. Similarly, individual optimization showed maximum drop strength as 100% at optimized process variables (66.2 MPa drop strength, 20% binder ratio and 0.520 mm average particle size) (Fig. 5.4b).

Regression equations (Table 5.6) were utilized to predict the maximum desirable outputs, drop strength and compressive strength (Fig. 5.4). Projected optimal level of molding pressure, binder ratio and average particle size to maximize compressive strength and drop strength showed optimal desirability (>0.99). The maximum compressive strength for individual optimization was determined as 14.8 MPa at optimized process variables (78.5MPa molding pressure, 20% binder ratio and 0.539 mm average particle size) as represented in Fig. 5.4a. Similarly, individual optimization showed maximum drop strength as 100% at optimized process variables (66.2 MPa drop strength, 20% binder ratio and 0.520 mm average particle size) (Fig. 5.4b).

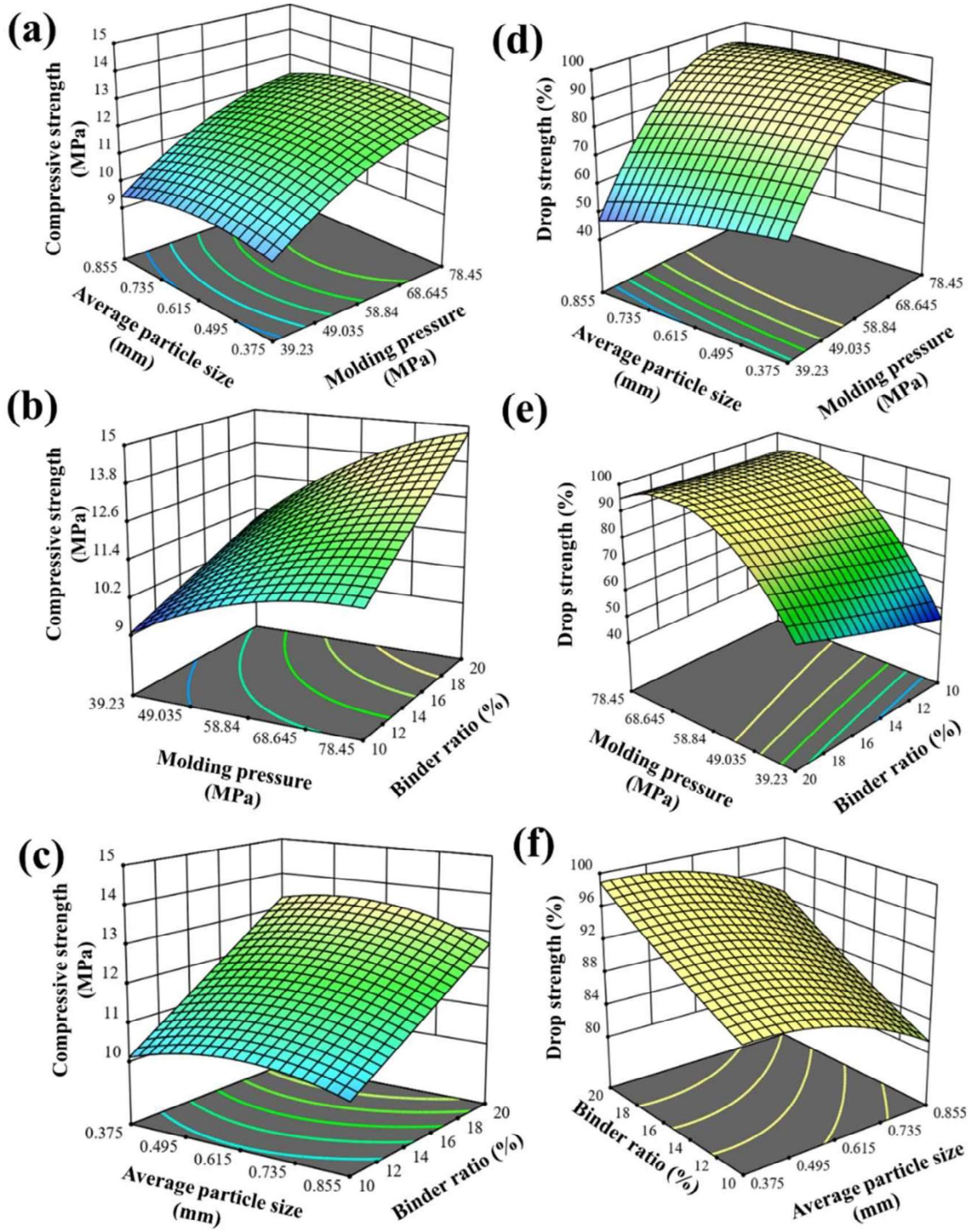

Fig. 5.3 Three-dimensional response surface plot of compressive strength (a-c) and drop strength (d-f) for microalgae blended coal composite (MBCC) production with varying molding pressure (MPa) vs average particle size (mm), molding pressure (MPa) vs binder ratio (%), average particle size (mm) vs binder ratio (%) respectively; the third variable was kept at central value.

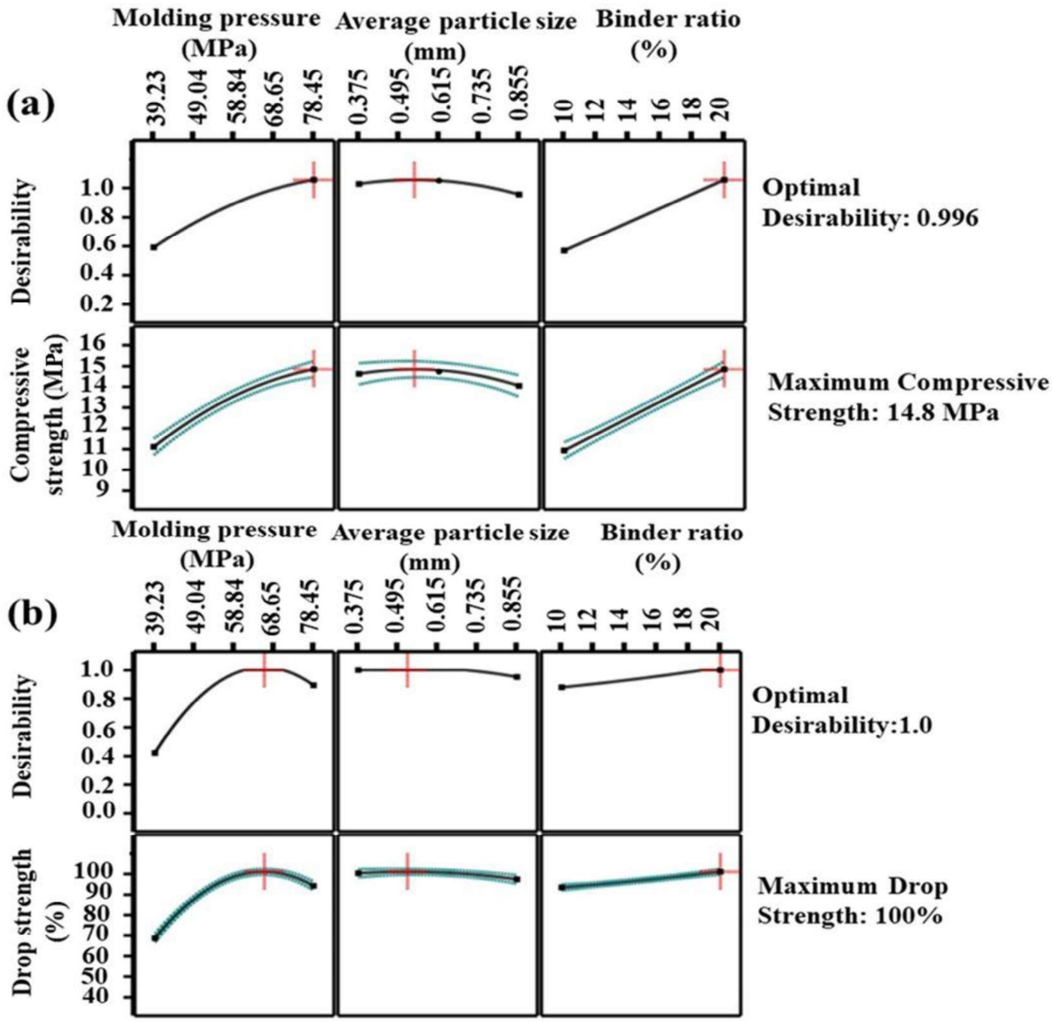

Fig. 5.4 Individual optimization plot to maximize (a) compressive strength (b) drop strength for microalgae blended coal composite (MBCC) production.

5.3.4 Multi-response optimization analysis

For simultaneous optimization, multi-response optimization analysis provides a compromise solution by combining all different response requirements into one composite requirement. The integrated contribution of three process variables (molding pressure, binder ratio, and average particle size) were analyzed to maximize the desired responses, such as drop strength and compressive strength. As an effective tool, the desirability function was utilized to analyze optimal conditions for multi-objective optimization (Fig. 5.5).

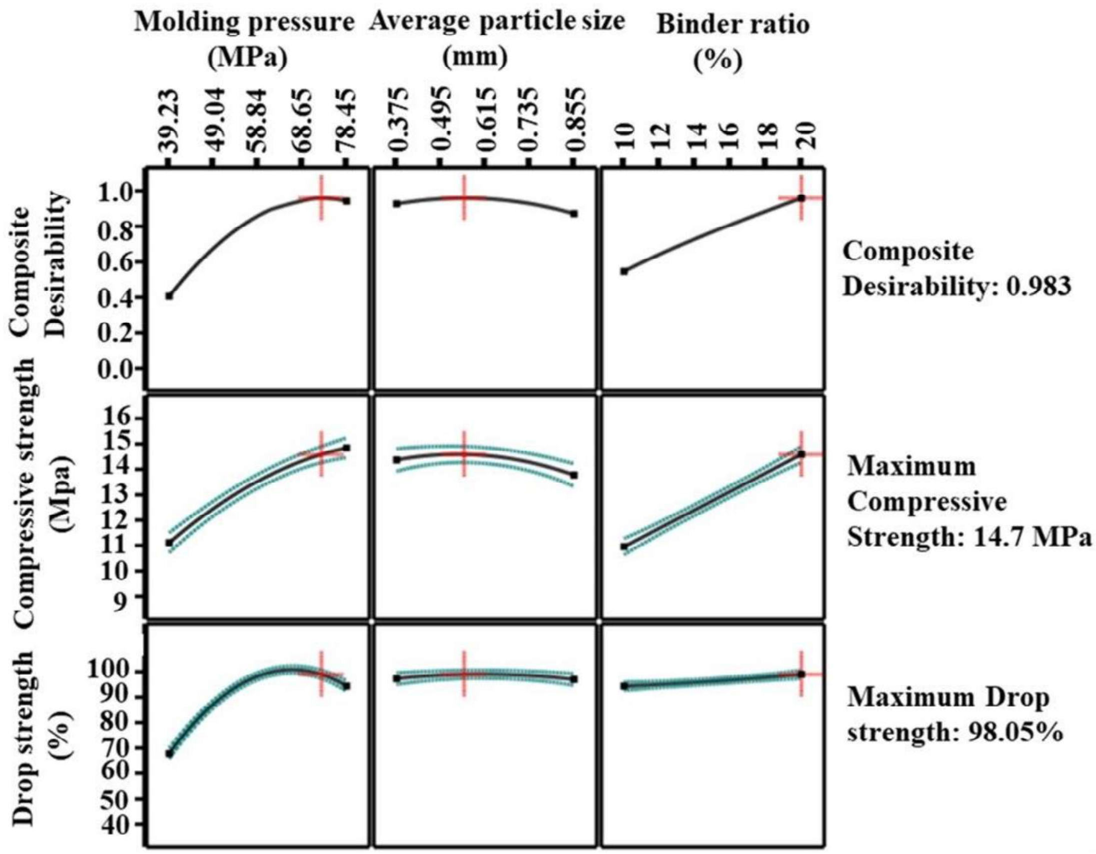

Fig. 5.5 Multi-objective optimization plot to maximize compressive strength and drop strength for microalgae.

The maximum predicted response values were obtained to be 98.05% drop strength and 14.7 MPa compressive strength at an optimum level of variables, 74.5 MPa molding pressure, 0.559 mm average particle size, and 20% binder ratio ($R^2 > 0.99$). The overlaid contour plot was established to visualize a common feasible region to maximize both responses (Fig. 5.6). The intersected white area in Fig. 5.6 represents the combined component proportions of two control factors among molding pressure, average particle size, and binder ratio that maximizes the desired outputs. As a limitation, only two experimental factors were considered simultaneously for 3D or 2D diagram representation under optimized conditions.

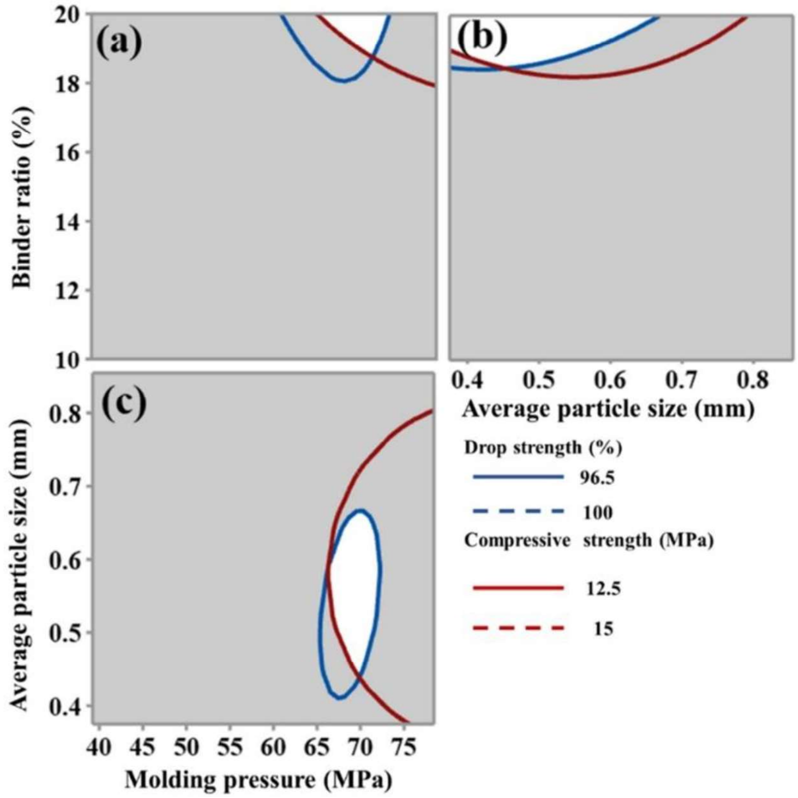

Fig. 5.6 Contour plot for cumulative maximization of responses with varying variables, (a) molding pressure (MPa) vs binder ratio (%) (b) average particle size (mm) vs binder ratio (%) (c) molding pressure (MPa) vs average particle size(mm); the third variable was kept at central value.

5.3.5 Model validation

Experiments were performed to measure the compressive strength, drop strength, and WRI at the predicted optimal value of process variables to validate the developed models for single and multi-optimized responses. Assessments of all parameters from individual and multi-response optimization, along with initial conditions, are summarized in Table 5.9. Compressive strength, in multi-objective optimization, reached 14.6 MPa compared to 12.0 MPa at initial conditions; similarly, drop strength reached up to 97.8% (92.0% at the initial condition). Further, WRI was also examined with a value of 79.0% at multi-response optimization compared to initial conditions (71.0%).

Therefore, multi-objective optimization was more significant than a single response to improve compressive strength and drop strength simultaneously with 21.7% and 6.3%, respectively (compared with initial conditions). These conditions also significantly enhance WRI (11.3% more than the initial conditions). A previous study by Gaqa and Watts (2018) reported 81.3% WRI of coal-algae pellets (80:20), which is very near to the current study. Polyvinyl alcohol–blended lignite briquette is reported with a drop strength of 98.72%, which is very close to 97.8% (drop strength of current study) (Guo et al., 2020). This data indicates the close similarity of microalgae with these synthetic binders. The compressive strength of wheat straw pellets (10.38 MPa) (Zhang et al., 2020), pine needles (7.05 MPa) (Mandal et al., 2019), carbonized water hyacinth (1.87 MPa) (Carnaje et al., 2018), and coal-molasses-pitch (9 MPa) (Manyuchi et al., 2018) is lower than MBCCs of the current study (14.6 MPa).

Therefore, the enhanced mechanical performance of MBCCs shows the effectiveness of microalgae as a binder for coal densification. Considering the application aspect, these blended solid fuels provide additional strength to minimize mass loss during the transfer from conveyor belts to bins, hoppers, feeders, and off-trucks to the final destination.

5.3.6 Fourier transform infrared analysis

FTIR spectroscopic analysis of raw coal, de-oiled microalgae biomass, and microalgae-blended coal composites, MBCC-1 (prepared at single-optimized response conditions for compressive strength), MBCC-2 (prepared at single-optimized response conditions for drop strength), and MBCC-3 (prepared at multi-optimized response conditions) were carried out to examine their structural features and impact of microalgae-coal interaction (Fig. 5.7).

Table 5.9 Comparison of mechanical performance of prepared composites in initial, individual and multi-objective optimized conditions.

Control condition	Molding Pressure (MPa)	Average particle size (mm)	Binder ratio (%)	Mechanical characteristics*			% Improvement in mechanical characteristics (compare to initial condition)		
				CS (MPa)	DS (%)	WRI (%)	CS	DS	WRI
Initial	58.8	0.62	15	12.0	92.00	71	-	-	-
Individual response optimization									
Compressive Strength	78.5	0.54	20	14.8	95.22	77	23.3	3.5	8.5
Drop strength	66.2	0.52	20	13.3	100.00	78	10.8	8.7	9.8
Multi-objective optimization	74.5	0.55	20	14.6	97.8	79	21.7	6.3	11.3

CS: Compressive strength; DS; Drop strength; WRI: Water resistance index. *All-observed values of responses were mean values of duplicates and standard deviation less than 3%.

Similar to most evolved coal, present raw coal showed peaks in 2960 and 3030 cm^{-1} (assigned for methyl groups linked to alkyl chains) and multiple peaks between 3000 and 2800 cm^{-1}, which are assigned for aliphatic chains, as the main constituent of low rank coals (Song et al., 2019). Further, O–H groups stretching vibration at 3600–3000 cm^{-1} is also reported for coal studies (Das et al., 2015). Oxygen-containing function groups such as alcohols, phenols, and C–O–H in phenolics correspond to peaks around 1300–1000 cm^{-1} (Song et al., 2019). Similarly, peaks at 1437 and 1586 cm^{-1} are assigned for aromatic heterocyclic groups (Mandal et al., 2019). The absence or low intensity of peaks around 2921 cm^{-1} directly indicates less proportion of methylene groups, as observed in low rank coals (Das et al., 2015). Random peaks between 1100 and 500 cm^{-1} are attributed to minerals in coal such as quartz, illite, kaolinite, and montmorillonite groups of minerals (Das et al., 2015).

In FTIR spectra of pure microalgae, prominent peaks were observed at 1700–1500 cm^{-1} with sharp intensity due to N–H, υC = N, and υC = O bending assigned for amide I, amide II, and carbonyl bonding from proteins (Gai et al., 2015). Sharp peaks in the 3000–2800 cm^{-1} range indicate lipid content increment (Ibarra et al., 1996). Further, peaks around 1200–900 cm^{-1} are attributed to carbohydrate content (Ibarra et al., 1996). The functionality of aromatic nitro compounds, carbonate ions, and C = C–C aromatic ring stretching corresponded by small bands nearly 1500–1200 cm^{-1} (Chyuan et al., 2020). Previously, some characteristic bands for lipids (1480–1350 cm^{-1}, 1770–1710 cm^{-1}, and 3025–2800 cm^{-1}) are identified in the FTIR spectra of microalgae, *N. oceania* (Zhao et al., 2022).

In assertive agreement with this study, the appearance of a sharp peak at 1350 cm^{-1} (assigned for lipid content) in FTIR spectra of microalgae and MBCCs indicates a significant influence of microalgae content in MBCCs (Magida et al., 2022). Major structural features between MBCCs and coal are identical (Fig. 5.7). Appearance of the sharp peak at 1350 cm^{-1} (assigned for lipid content) and 1647 cm^{-1} (assigned for amide-I bonds) indicates a better impact of microalgae, which are absent in raw coal spectra. Further, the peak at around 1586 cm^{-1}, present in raw coal spectra, is absent in coal composites due to the breaking of C = C and the formation of new bonds (Fermoso et al., 2018). The presence of peaks for organic sulfates (at 1230 cm^{-1}), thiols (at 685 cm^{-1}), and ammonium ions (at 3030 cm^{-1}) provide strong evidence of microalgae binding with coal in the form of composites (Li et al., 2018). The summary of FTIR characterization is provided in Table 5.10.

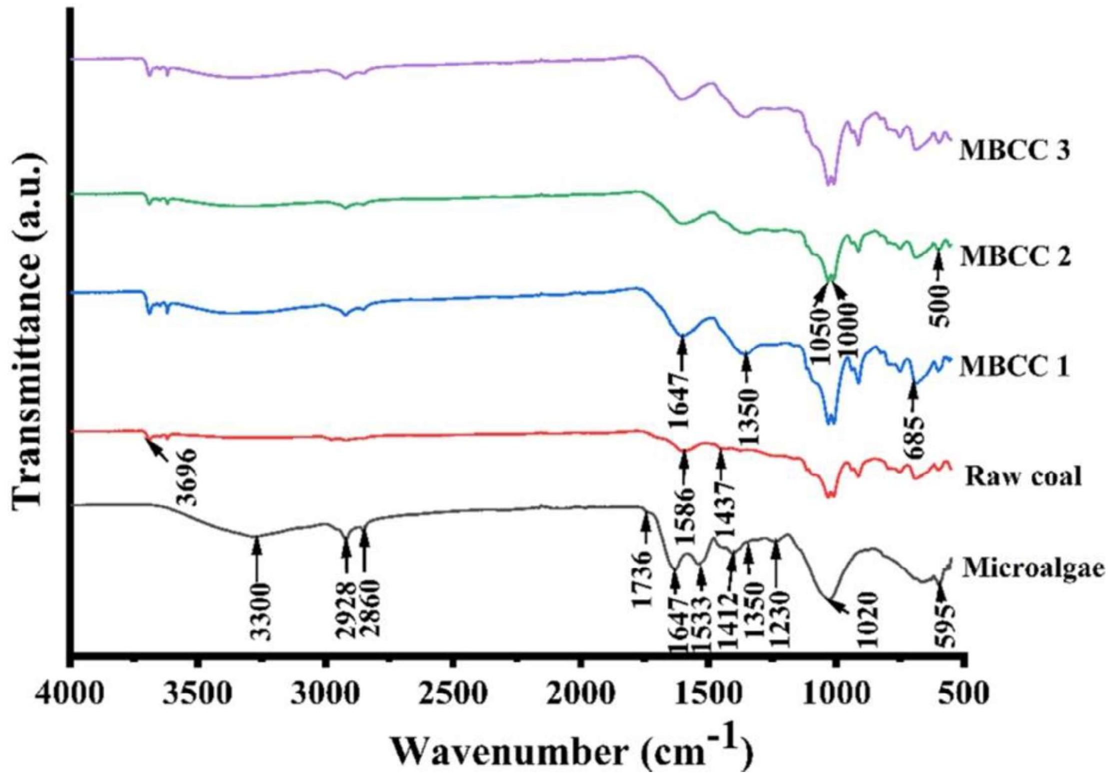

Fig. 5.7 FTIR spectra of microalgae, raw coal, individual optimized and multi-objective optimized microalgae blended coal composite (MBCC): MBCC1 (for compressive strength optimization), MBCC2 (for drop strength optimization), MBCC3 (for multi-objective optimization).

Table 5.10 Summary of FTIR characterization of low rank coal, de-oiled microalgae biomass, and MBCCs (MBCC1, MBCC2, and MBCC3).

SI. No.	Sample	Wavenumber (cm^{-1})	Band assignment
1.	Coal	3600 - 3000	Presence of O-H groups stretching vibration
		3000-2800	Aliphatic C-H group with stretching vibration for CH_4 (2959 cm^{-1}), CH_3 (2864 cm^{-1}) and CH_2 (2921cm^{-1})
		1800-1000	Multiple peaks assigned to oxygen containing, esters and carboxylic acids with keto group (1350 cm^{-1}) and aromatic C=C (1586 cm^{-1})
		1150-1033	Multiple peaks assigned to C-O (1150 cm^{-1}), ether (1150 cm^{-1}) and alcohol (1033 cm^{-1})
		Below 1000	Aromatic C-H group with deformation vibration of benzene ring (900-700 cm^{-1}), presence of quartz and kaolinite (500- 1100 cm^{-1}) and Si-O bending vibration (471 cm^{-1})
		876-776	Presence of aromatic C-H group
2.	De-oiled Microalgae	3300	Presence of (O-H) and (N-H) groups of water, protein and carbohydrate

		2920-2850	Symmetrical (2850) and asymmetrical (2920) stretching of methylene groups (CH_2) of lipids
		1744	Symmetrical stretching of C=O of ester functional group from lipids and fatty acids
		1647	C=O stretching related to amide-I bonds
		1542	C-N stretching related to amide-II bonds
		1480- 1350	Assigned for lipid content
		1200-900	Asymmetrical stretch of C-O-C of polysaccharides
		1077	Asymmetrical stretch of C-O-C of triglycerides, cholesterol esters, and ethers.
3.	MBCCs	3500	O-H groups stretching related to presence of water
		3100-2800	CH_4 evolution, C-H stretching
		1800-1100	C-H stretching, C-N stretching and O-H bending to form new bonds
		1647	Presence of amide-I bonds (Absent in coal)
		1350	Assigned for lipid content (Absent in coal)

MBCCs: De-oiled microalgae blended coal composites.

5.3.7 Thermogravimetric analysis

The qualitative and quantitative thermal decomposition behavior of any solid fuel can be determined by using thermogravimetric methods. The TGA-DTG-DTA of the low rank coal, de-oiled microalgae biomass and MBCCs, and their morphological appearance are represented in Fig. 5.8a–f. Curves were analyzed in three stages: 21–200 °C (stage 1), 200–600 °C (stage 2), and 600–1000 °C (stage 3). During the initial stage (21–200 °C) of weight loss, the dehydration process occurred to release free and inherent moisture with mass loss rates of 6%, 8%, 15%, 7%, and 8% in raw coal, microalgae, and MBCC-1, MBCC-2, and MBCC-3, respectively. Similar results are reported in the literature for *C. vulgaris* (Azizi et al., 2017). The different intensity and width of first-stage DTG peaks were observed in coal and microalgae, including the irregular weight loss pattern in MBCCs due to non-uniform mass transfer effects (compared to coal and microalgae) (Chen et al., 2012). In assertive agreement with Sun et al. (2014), the current study showed heterogeneous and irregular combustion in coal with a higher fuel ratio of 2.86. Conversely, homogeneous and smooth combustion can be observed in microalgae (fuel ratio 0.79).

Additionally, coal rank, particle size, volatile matter content, and microalgae blending ratio are vital factors that affect combustion behavior (Sun et al., 2014). In the second stage (200–600 °C), a strong DTG peak contributed to the main decomposition stage with a decomposition rate (DTG_{max}) of − 0.5%/min for microalgae, − 0.23%/min for coal, and nearly similar for MBCCs (− 0.18%/min to − 0.24%/min). The thermal reactivity of *C. pyrenoidosa* with DTG_{max} of − 0.5%/min was observed to be higher than reported for *Tetraselmis suecica* (− 0.4%/min) (Tahmasebi et al., 2013) and *S. platensis* (− 0.31%/min) (Gai et al., 2015). In this stage, microalgae with maximum weight reduction (68%) exhibited a strong peak at 312 °C corresponding to the combustion of protein and carbohydrates (Kang et al., 2019). The DTG profile of *C. pyrenoidosa* in the current study showed multiple short peaks, which is very similar to *C. vulgaris* (Azizi et al., 2017) (Fig. 5.8b).

Coal and its composites with more stable aliphatic hydrocarbons, alkyl naphthalene, alkyl benzenes, and oxygen bearing heterocycle groups were decomposed at 350–600 °C (Jankovic et al., 2020). This region liberated volatile matter and covalent bonds as ether and methylene groups to release hydrogen, carbon monoxide, and lighter hydrocarbon (Qi et al., 2017). In opposite to coal with one sharp DTG peak (DTG_{max} at 464°C) in the second stage; MBCCs showed two peaks (one short at 260–280°C, and one sharp with DTG_{max} at 458–462°C). Further, the third, terminating stage (600–1000°C), showed very less weight reduction in microalgae compared to coal and MBCCs. (Fig. 5.8b).

In microalgae combustion, most organic matter was decomposed in the main pyrolysis stage (second) and carbonaceous residue in the third stage. Characteristic temperatures, i.e., ignition temperature (Ti), peak temperature (Tp), and burnout temperature (Tb), are summarized in Table 5.11.

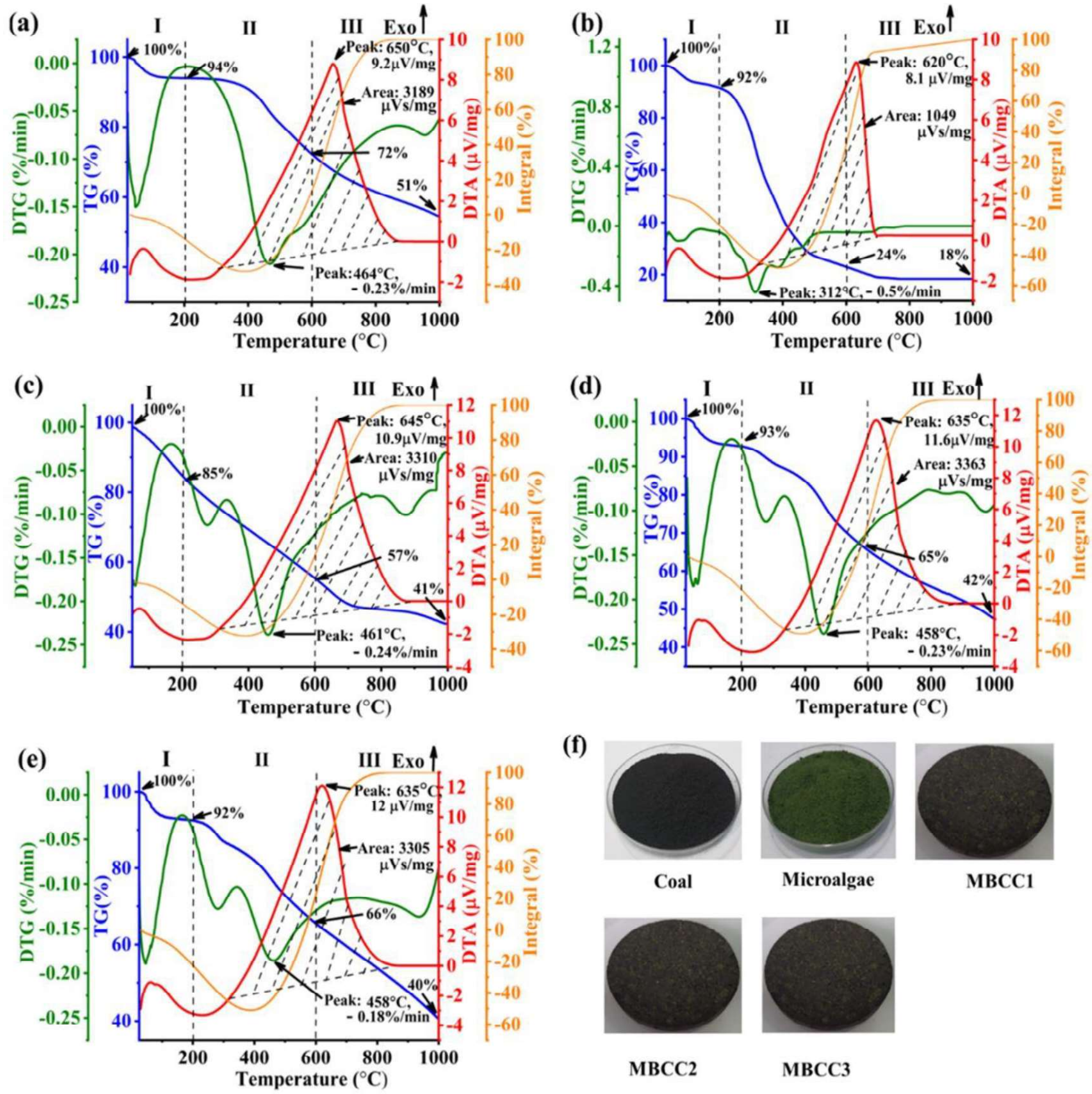

Fig. 5.8 TGA-DTG-DTA plot of (a) raw coal (b) microalgae (*C. pyrenoidosa*) (c) individual optimized MBCC1 (for compressive strength optimization) (d) individual optimized MBCC2 (for drop strength optimization) (e) multi-objective optimized MBCC3 (f) morphological appearance of raw coal, microalgae, and MBCCs.

Microalgae have lower ignition and burnout temperatures than coal, which interprets higher combustion reactivity of microalgal biomass. A similar combustion trend is also observed in *C. vulgaris* with a burn-out temperature of 545 °C (Azizi et al., 2017). Characteristic points of MBCCs were slightly shifted towards microalgae, with suitable ignition points (nearly 300 °C) and extended burning temperature (47–82 °C), indicating the thermal behavior upgradation of coal-algae composites. To measure heat evolution during combustion, DTA analysis showed an almost similar pattern with strong exothermic peak for microalgae (620 °C), parent coal (650 °C), and MBCCs (630–645 °C) with slight variation (Fig. 5.8a–e). The peak for pure microalgae is sharper than coal and its composites due to high lipid content (Kang et al., 2019). A single exothermic peak reflects the heterogeneous ignition mechanism of coal and its composites with the liberation of volatile matter from pores and prolonged char combustion (Sun et al., 2014).

Unlike combustion in oxygen, pyrolysis in nitrogen, coal decomposed slowly with extended peak and combustion temperatures. The peak area under the DTA curve showed a minimum area (1049µVs/mg) for microalgae and 3189µVs/mg for coal. Further, an expanded area (3305–3363µVs/mg) was observed for composites in agreement with previous DTA studies (Das et al., 2015). Mechanical and thermal performance assessment of different reported densification studies, along with the present study is summarized to analyze the impact of binder (Table 5.12).

Table 5.11 Combustion characteristics of the low rank coal, de-oiled microalgae biomass and MBCCs at different optimization conditions.

Samples (Heating rate- 10°C/min)	Weight loss (%)			Residual mass (%)	Characteristic temperature points (°C)			DTA characteristics	
	Stage-I	Stage-II	Stage-III		Ti	Tp	Tb	Peak temperature (°C)	Area covered (µVs/mg)
Raw coal	6	22	21	51	335	464	803	650	3189
Microalgae	9	68	5	18	240	311	474	620	1049
MBCC1	15	28	16	41	298	461	850	645	3310
MBCC2	7	28	23	42	301	460	885	635	3363
MBCC3	8	26	26	40	299	462	875	630	3305

Ti: Ignition temperature; Tp: Peak temperature; Tb : Burnout temperature; MBCCs: Microalgae blended coal composites; MBCC1: MBCCs at compressive strength optimization condition; MBCC2: MBCCs drop strength optimization condition; MBCC3: MBCCs at multi-objective optimized condition.

Table 5.12 Comparative performance assessment of different coal-biomass densification studies.

Study detail	Processing material	Binder	Mechanical performance	Thermal properties	Reference
Production of low rank coal fines nodules	Coal samples from the Konya coalfield, India	Carboxy methyl cellulose (10%) with lime (10%)	CS: 376 – 448 N	CV: 25.15 MJ/kg Ti :336 – 408˚C Tp :452 – 478˚C Tb :527 – 562˚C	(Das et al., 2015)
Bituminous coal briquette production	Bituminous coal, Mezino I coal field, Iran	Beet pulp (20% Tar (10%)	CS: 0.401- 0.816 MPa WRI: 73.45-90.44%	CV 27.82 MJ/kg	(Azizi et al., 2017)
Pelletising of Coal- algae (*Scenedesmus*)	Bituminous coal, South Africa	*Scenedesmus*-Microalgae (10%-20%)	CS: 6.86 - 17.64 MPa WRI: 65.5- 88.9 %	CV 24 MJ/kg	(Kan et al., 2016)
Briquettes of coal slime blended with waste feedstock	Coal slime, compressor oil/ straw/ sawdust/ peat	Starch (5%)	Mass retention 78 -98% DS 1.3-4.3 (out of 15)	Ti :350-607˚C Tb :1019-1075˚C	(Onaji et al., 1993)
Cow dung–blended wheat straw and rice husk biomass pellets	Wheat straw, rice husk and cow dung	Molasses (0 –100%)	Durability 50 – 97%	CV 14.97 MJ/kg Energy density 19627 MJ/m^3	(Iftikhar et al., 2019)
De-oiled microalgae biomass (*C. pyrenoidosa*) blended low rank coal composites	Low rank coal fines, Amelia coal block, Singrauli coalfield, India	*C. pyrenoidosa* (10 – 20%)	Bulk density 1100 kg/m^3 CS: 9.2 – 14.7 MPa DS: 46.1 – 97.75% WRI 71 – 79%	CV 18.62 MJ/kg Ti: 298 – 301˚C Tp: 460 – 462˚C Tb: 850 – 885˚C Heat involved: 3305 – 3363 µVs/mg	Present study

CS: Compressive strength; DS: Drop strength; WRI: Water resistance index; CV: Calorific value; Ti : Ignition temperature; Tp:Peak temperature; Tb: Burnout temperature.

5.3.8 Artificial neural network simulation

The complexity of thermal analysis enhances with biomass blending due to heterogeneous combustion. In this direction, artificial intelligence, different machine learning tools, provides a realistic interpretation of heterogeneous combustion without undergoing rigorous modeling approaches (Rasool et al., 2021). ANN models were developed to predict and validate the thermal decomposition analysis of raw feedstocks (coal/microalgae) and multi-optimized MBCCs.

The ANN performance plots for coal, microalgae and composites were shown for training, validation, and testing stages (Fig 5.9). The R^2 value for all feedstocks was close to 1, indicating excellent agreement between model-predicted and experimental data. To achieve the best performance of the model, sufficient iterations were executed. According to Fig. 5.10 a–c, the minimum value of mean squared error is near 0 (10^{-4}–10^{-8}) for coal, microalgae, and composites at different iterations (330–1000). Further, the error histogram plots for coal, microalgae and composite are shown (Fig. 5.11a–c). The non-significant error can be observed for coal (-0.06×10^{-2} to 0.31×10^{-2}), microalgae (-0.16×10^{-3} to 0.07×10^{-3}) and composites (-0.86×10^{-4} to 0.22×10^{-4}).

Overall, the developed model accurately predicts the thermal decomposition of microalgae-coal-blended solid fuels. A similar level of accuracy is also observed in the thermal decomposition of *C. vulgaris*–blended peanut shell mixture at different heating rates (Bong et al., 2020). This study suggests that the developed ANN model ($2 \times 18 \times 1$) might be used to establish the relationship between input-output data, error analysis and output prediction of thermal decomposition of blended fuel feedstocks.

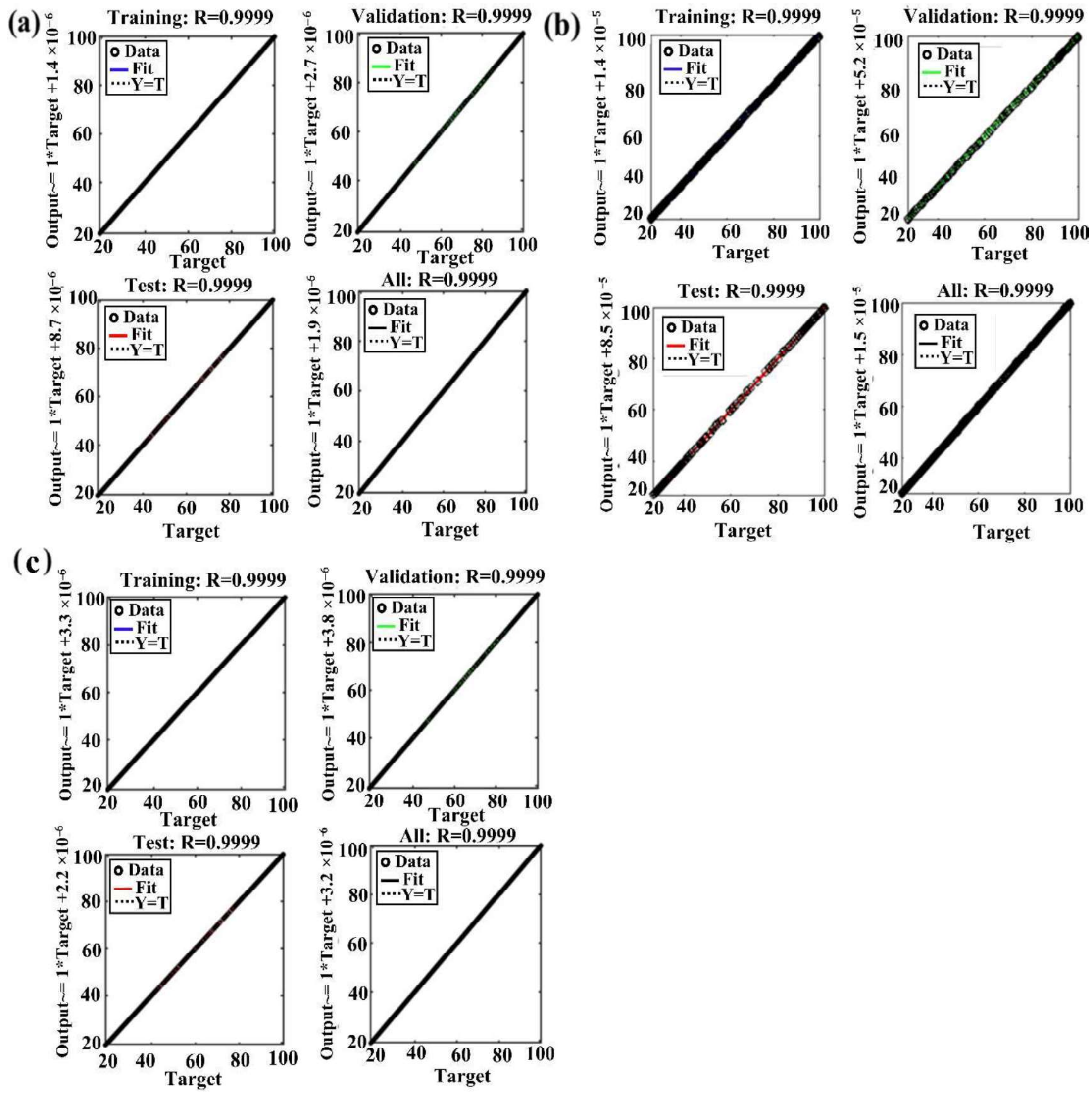

Fig. 5.9 ANN Regression plots of training, validation and testing stages (a) coal (b) de-oiled microalgae (c) multi-objective optimized microalgae blended coal composite, respectively.

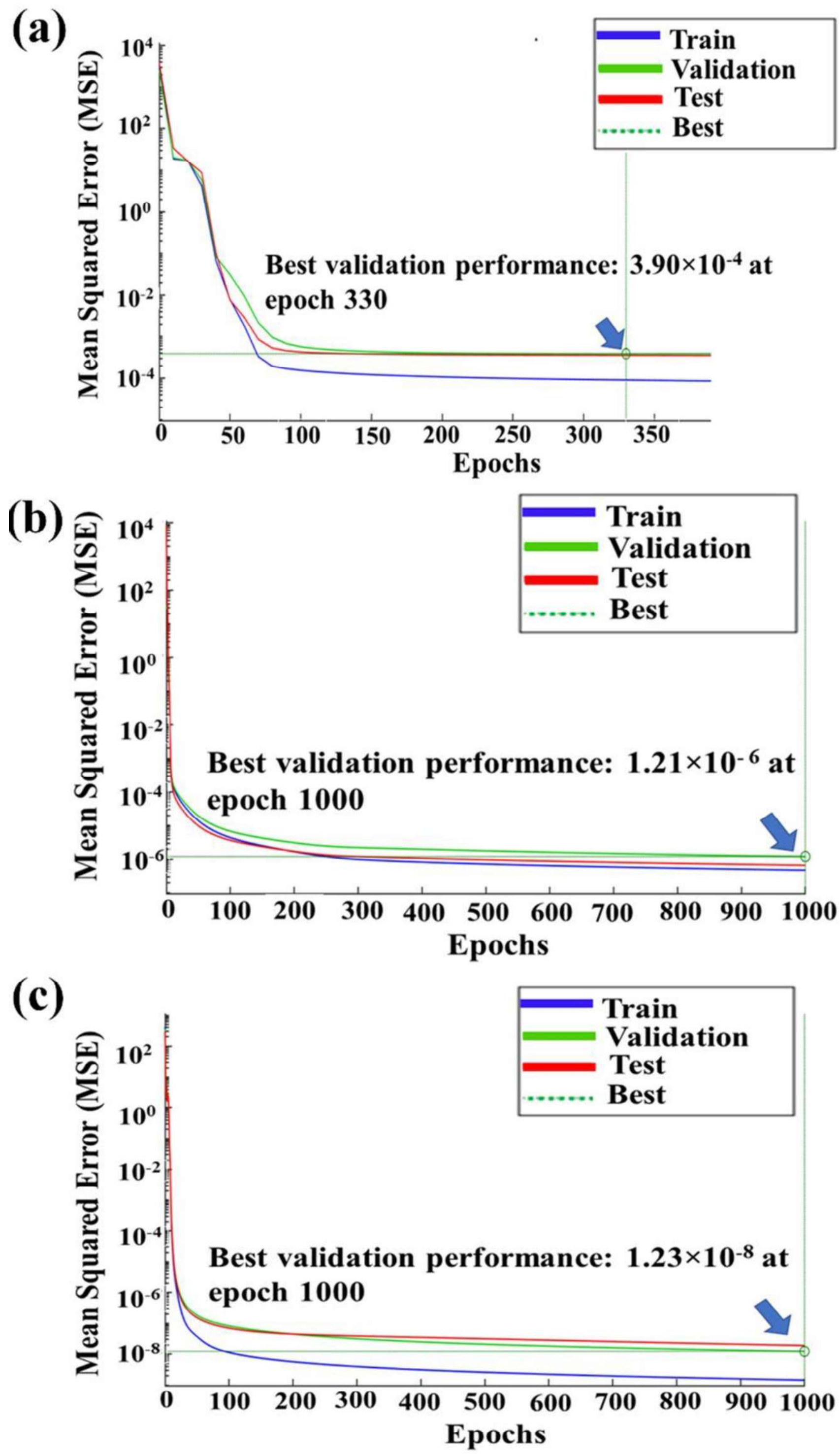

Fig. 5.10 Validation performance of mean square error (MSE) for TGA data at a heating rate of 10 ºC/min and 18 neuron numbers (a) coal (b) microalgae (*C. pyrenoidosa*) (c) multi-objective optimized microalgae blended coal composite.

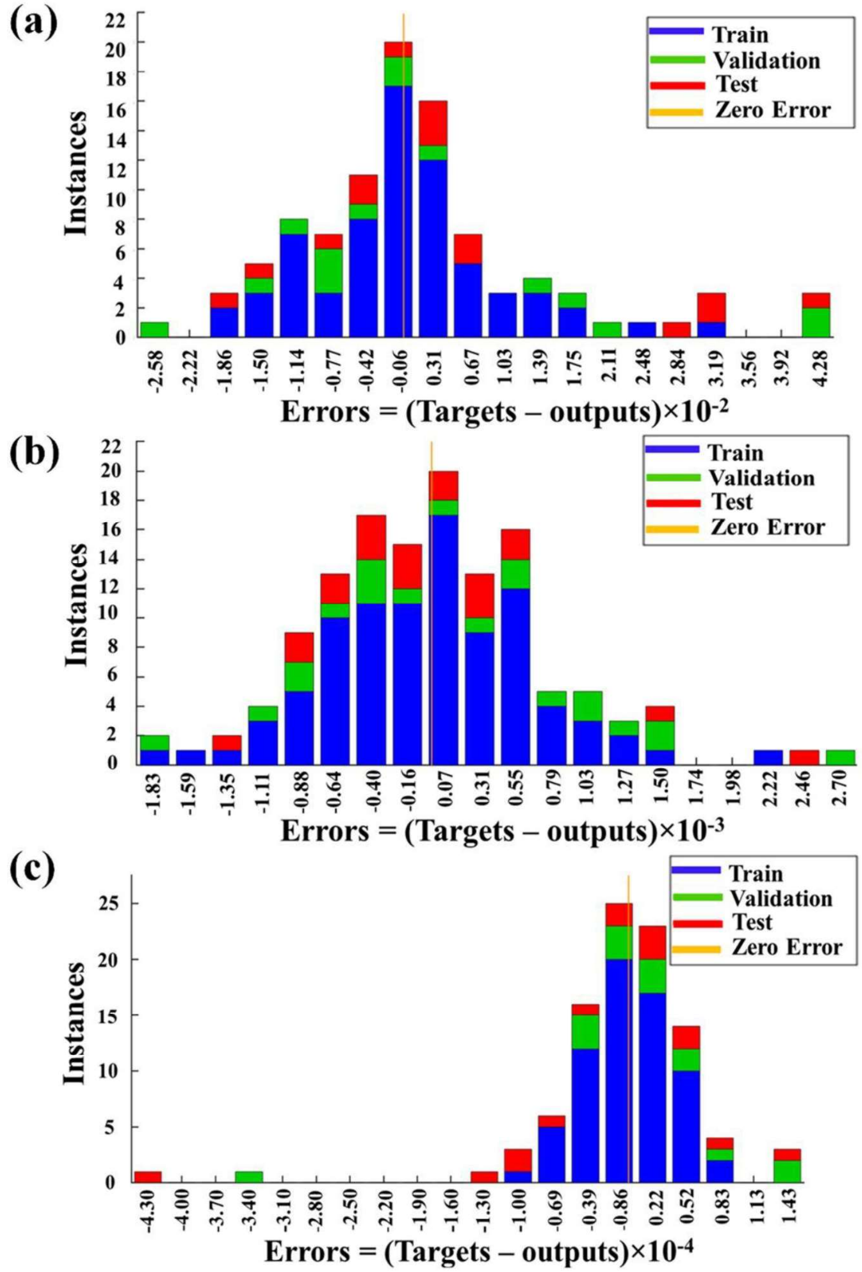

Fig. 5.11 Error histogram for TGA data at a heating rate of 10 ºC/min and 18 neuron numbers (a) coal (b) microalgae (*C. pyrenoidosa*) (c) multi-objective optimized microalgae blended coal composite.

5.4 Conclusion

The present study investigates the value-added interaction between the de-oiled biomass of *C. pyrenoidosa* and coal to improve the mechanical and combustion properties of pellets. The blended coal-biomass composites at multi-response optimization conditions showed ASTM standards of solid fuel production with compressive strength of 14.6 MPa and drop strength of 97.8%. FTIR studies reveal synergistic binding with coal and the direct impact of microalgae upon blended composites. TGA-DTG studies confirm the smooth ignition of single and multi-objective optimized composites (Ignition temperature of 298–301 °C with extended burnout temperature (850–885 °C). DTA results show more exothermic heat is evolved with single and multi-optimized composites (3305–3363 μVs/mg) than raw coal (3189 μVs/ mg). Finally, the developed ANN model (2 × 18 × 1) is used to accurately predict the thermal decomposition of the individual (coal and microalgae) as well as blended composites with $R^2 > 0.9999$. The direct application of biomass-blended coal composites in boilers must be crucially investigated for optimum boiler efficiency with the lowest pollutant emission. In this regard, biomass-responsive boilers with steady, automatic feeding operation are recommendable for clean and efficient fuel burning, which profoundly depends upon the quality of coal and biomass as calorific value, moisture, ash, and fixed carbon content. The coal-biomass-blended energy production processes are also getting attention like other biomass based renewable energy production processes due to the scalability, economical and fed biomass availability. The co-combustion investigations of coal-biomass blends encourage further exploration of tri-fuel blends by mixing coal and de-oiled biomass with waste feedstocks such as municipal solid waste, plastic waste and cattle dung. Modern approaches such as ANN, deep learning, and other machine learning approaches will facilitate a more rapid and reliable interpretation of concerns with combustion behavior, boiler efficiency and toxic gas emission during combustion. Further sustainable energy development approaches encourage pilot and plant scale investigations of co-combustion (coal-biomass) and tri-fuel (coal-biomass-waste) combustions.