Chapter-6
Geochemical Characterization of coal

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6.1 Introduction

Coal is a mixture of organic and inorganic compounds. Its organic components are derived from various parts of plants such as wood, leaves, pollen and spores, etc. which undergoes biochemical and physico-chemical changes with the passage of time and evolve as coal (Dai et al. 2020). Due to heterogeneous in nature of coal, several analytical techniques were involved for its characterization and study. The qualitative assessment of coal with respect to rank, grade and type along with chemical constituent is important to know especially its proximate, ultimate and calorific components. Proximate analysis is one of the simplest and oldest methods for the chemical characterization of coal (Suárez-Ruiz and Ward 2008). It provides robust parameters for the qualitative and quantitative evaluation of inorganic (ash and moisture) content and organic content (fixed carbon and volatile matter) of coal. Several other parameters also help in coal characterization and its utilization.

The ultimate components of coal include major elements such as carbon, hydrogen, nitrogen, sulfur and oxygen for a better understanding the nature of organic matter in coal. The calorific value plays a crucial role in deciding factors for coal utilization in terms of coal grade for thermal industries. Coal grade is highly valuable for consumers and producers of coal. The gradation of non-coking coal is based on gross calorific value (GCV). These grades are divided into seventeen, from G-1 (highest GCV, greater than 7000 kcal/kg) to G-17 (lowest, exceeding 2200 and not exceeding 2500 kcal/kg) for Indian coals (Ministry of Coal, GOI 2014). Apart from organic content, the inorganic content of coal also play important role in coal utilization. Furthermore, inorganic components are classified in three groups according to their origin:

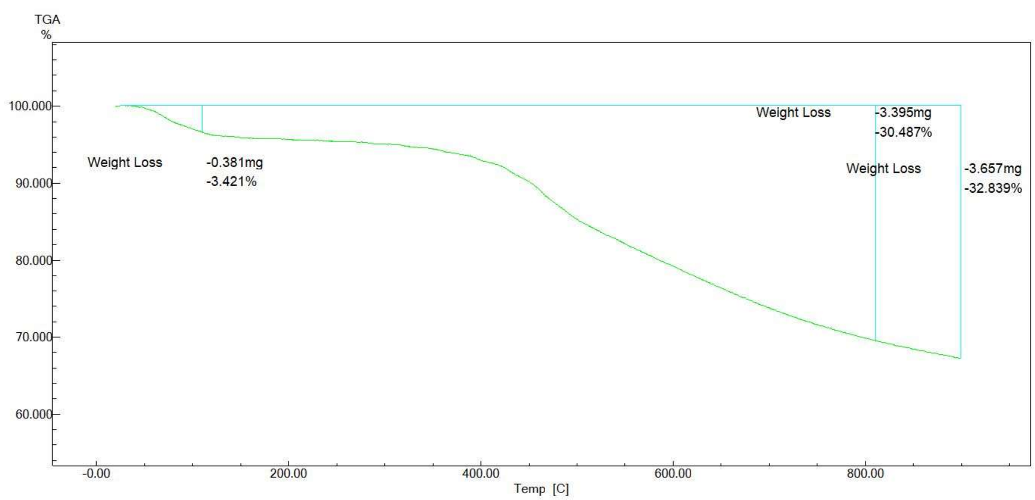
1. Inorganic matter from original plants
2. Inorganic and organic complexes and minerals which formed during the first stage of the coalification process. It is introduced by wind or water into the coal deposits during formation.
3. Minerals deposited during the second phase of the coalification process, after the consolidation of the coal, by ascending or descending solution in cracks, fissures or cavities or by alteration of primarily deposited minerals.

Mineralogical content and functional groups in coal which are determined by peaks and graphs can lead to the genesis of coal formation (Orem and Finkelman 2003). Elemental constituents are an important component in coal, which can be further deciding factors for the scope of study. Trace elements were also studied in geochemical characterization for coal samples. Surface morphology is also a part of the study, which is compared at the end of the leaching experiment to see the change in coal particles after the experiment in residue. In the present investigation a large number of samples (coal, shaly coal and coal ash) from Dhanpuri OCM, Sohagpur coalfield have been subjected to these analyses and their results have been used in rank, classification and potential utilization of coal.

6.2 Proximate analysis

This analysis has been carried out for the determination of moisture, ash, fixed carbon, and volatile matter percentage in samples. Traditionally, proximate analysis determination involves heating the sample in the furnace under ASTM or BIS standards specific conditions (ISO: 1350-1, 1984; ASTM D3172). The procedures for proximate analysis are rather empirical but do not require elaborate costly equipment. However, here we have also adopted the thermogravimetric analysis (TGA) for proximate analysis because traditional methods are not only time consuming but also it requires plenty of samples (in amount).

For TGA, the graph is plotted between the mass losses with respect to temperature. The mass losses from these curves were tabulated. The mass losses during analysis can be observed in three main stages: moisture evaporation, solid decomposition and devolatilization (Donahue et al. 2009). The first stage of mass loss is very slight,



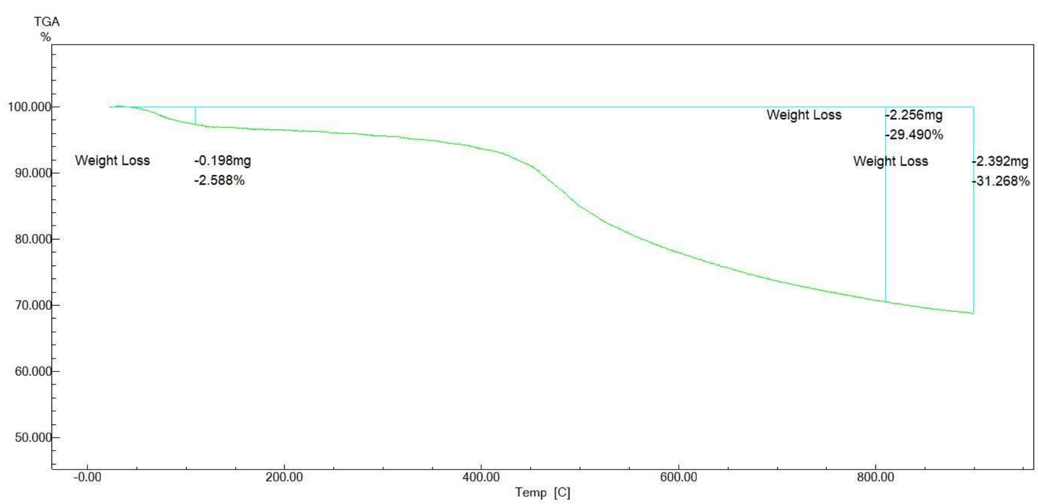


Fig. 6.1: Graph of weight loss by Thermogravimetric Analyzer (TGA) of proximate analysis for Sample No TA-1 and TA-2.

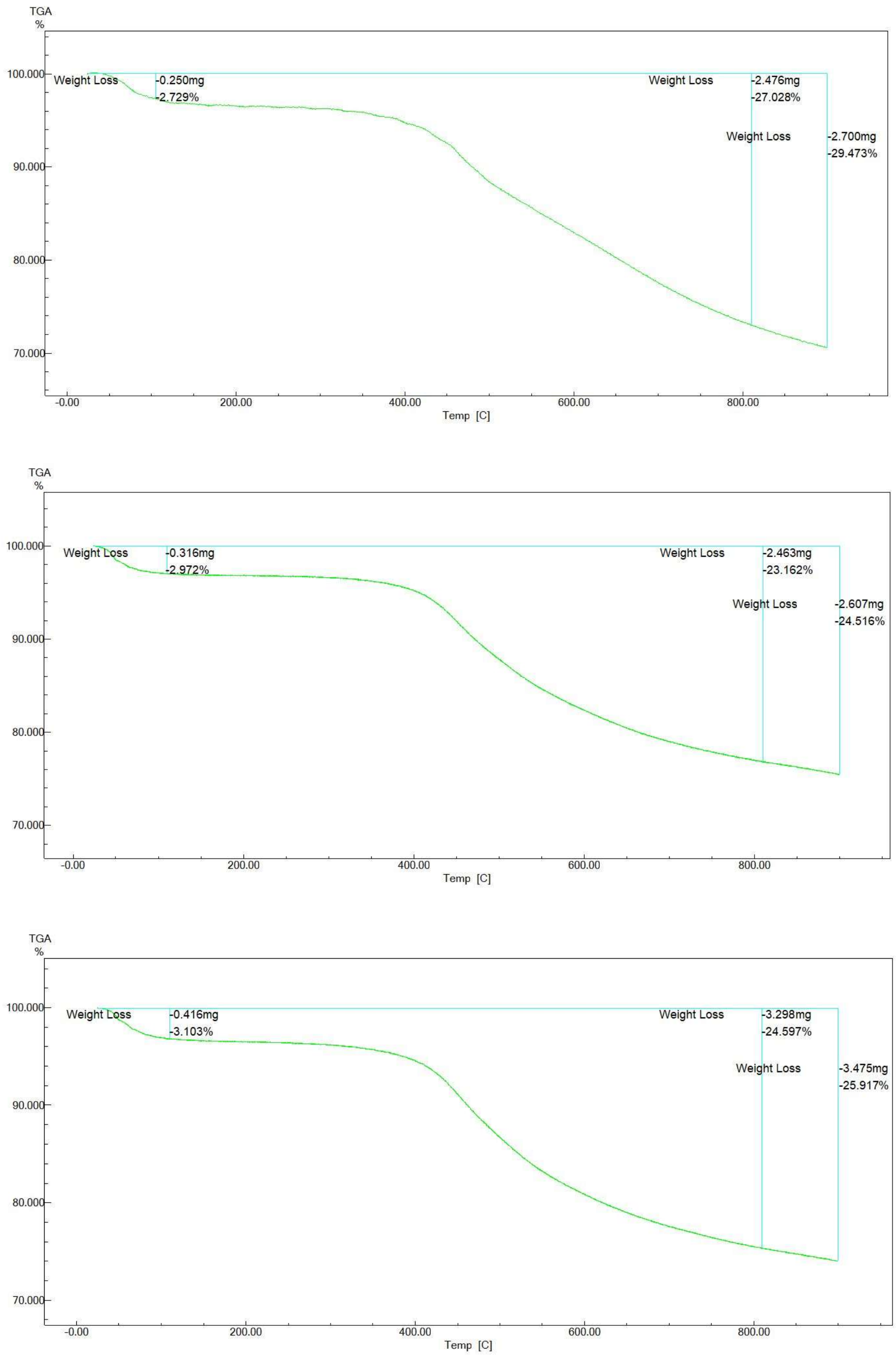


Fig. 6.2: Graph of weight loss by Thermogravimetric Analyzer (TGA) of proximate analysis for sample TC-1, TG-3 and TG-4.

caused by the elimination of moisture. In the second and third stages, i.e. devolatilization and solid decomposition caused significant mass losses, representing the leading part of the proximate analysis.

During coal analysis, the first stage occurred between room temperature and 102±5°C, where the mass loss was observed and varies from 2.59% to 3.42%. It can be seen in the graph that it takes sharp curvature before the plateau (Figs. 6.1 and 6.2). The plateau represents the constant weight up to 400°C. Further, increase in temperature leads to a drastic change in coal properties chemically and physically. This increase in temperature leads to the loss of organic matter and volatile matter from coals. The ash content in coal samples varies from 23.16% to 30.5%, while volatile matter varies from 24.51% to 32.84%. The fixed carbon varies from 33.25% to 49.36% which is calculated by {100-(Moisture% + Ash% + Volatile matter %)}.

The proximate analysis of coal sample in tables 6.1 and 6.2 revealed the variation of value among the samples in Dhanpuri OCM. Moisture percentage varies from 1.74-7.3, ash percentage varies from 9.65-34.21, volatile matter percentage varies from 15.98-36.26, and fixed carbon percentage content is calculated by subtraction of the sum of moisture, volatile matter, and ash contents from 100, varies from 33.96-69.55. Less ash contents of these coals show that it is of Steel Grade-II for steel grade and washery grade if coking property is present in coal samples. The gross calorific value of coal samples is from grade G9 to G6 according to the Indian grading system of coal (Ministry of Coal, GOI 2014).

6.3 Moisture

Moisture percentage varies from 1.74-7.3 in coal samples of the study area. The average value of moisture percentage is 3.32% in coal samples (Tables 6.1 and 6.2). Moisture in coal samples is almost consolidated except in GV 1 and GV 2, which is more than 5%. Rest all samples have a moisture percentage of less than 5%. It can also be seen in figures 6.4 and 6.5. The standard deviation (σ) and standard error of the mean for moisture are 1.10 and 3.30 for the coal samples the study area.

6.4 Ash

Ash percentage varies from 9.65-34.21 in coal samples of the study area. The average value of ash percentage is 16.95% in coal samples (Tables 6.1 and 6.2). The ash percentage in coal samples has little fluctuation in concentration. Even K1, T1 and GV1 cross the volatile matter percentage and fixed carbon percentage. The standard deviation (σ) and standard error of the mean for ash are 5.7 and 0.77 for coal samples.

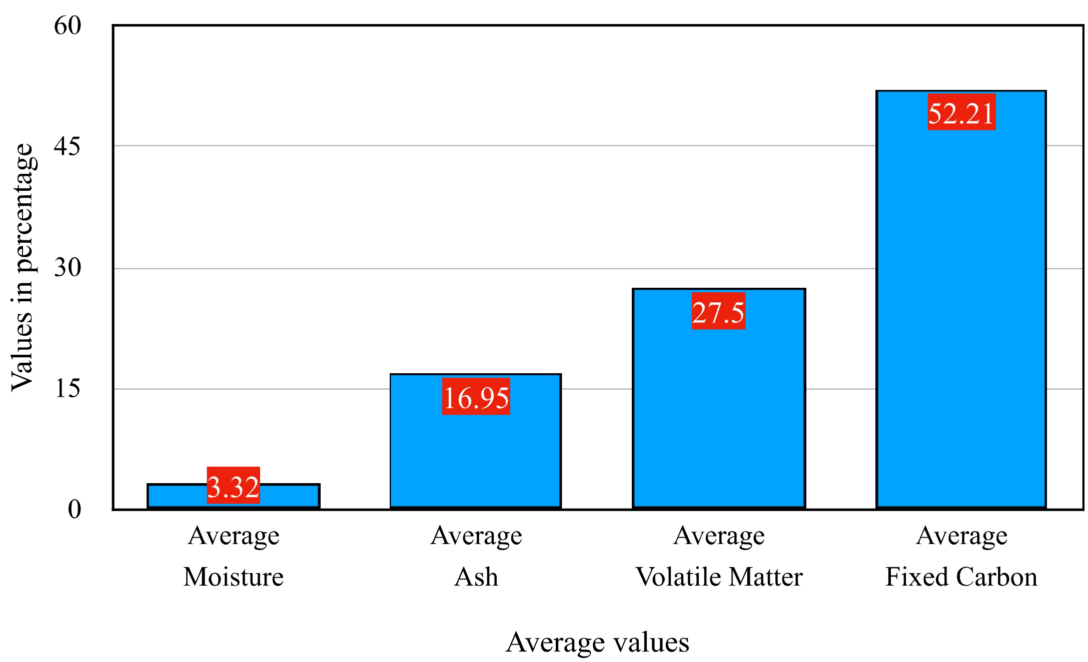


Fig. 6.3: Average value of moisture, ash, volatile matter and fixed carbon percentage in coal samples.

Sample Name	Weight %			
	Moisture	Ash	Volatile	Fixed Carbon
A1	3.52	13.77	32.62	50.08
A2	1.95	12.5	15.98	69.55
B3	2.34	20.6	29.60	47.45
C1	3.41	13.71	28.65	54.21
C2	3.43	12.64	29.42	54.49
C3	2.95	12.51	30.97	53.55
D1	3.86	14.65	32.49	48.98
E1	2.41	11.82	28.46	57.30
E2	2.03	10.55	29.93	57.48
F1	2.96	14.94	22.91	59.18
F2	2.61	13.6	24.57	59.20
G1	1.92	26.96	31.64	39.47
G2	1.74	23.09	30.70	44.46
J1	4.72	13.28	27.93	54.06
J2	3.51	18.38	25.09	53
K1	4.14	30.87	22.47	42.51
K2	4.76	13.15	29.55	52.52
L1	3.67	11.83	31.18	53.31
L2	4.69	9.65	29.96	55.69
L3	3.49	11.73	30.07	54.70
M1	3.50	18.48	27.62	50.38
M2	4.24	14.18	22.65	58.91
N1	2.89	17.04	30.56	49.49
N2	2.88	22.47	29.25	45.37
O1	2.82	16.14	26.59	54.42
O2	2.41	11.82	26.56	59.19
O3	2.02	14.94	33.69	49.33
P1	2.96	13.96	21.64	61.42
P2	2.61	26.96	28.65	41.76
P3	1.92	13.71	19.36	64.99

Table 6.1: Proximate analysis of coal samples

Sample Name	Weight %			
	Moisture	Ash	Volatile Matter	Fixed Carbon
Q1	1.74	13.77	22.36	62.11
Q2	3.53	12.64	29.36	54.44
Q3	1.84	12.63	30.36	55.15
R1	2.13	21.87	28.42	47.58
R2	3.98	15.35	31.54	49.13
R3	2.51	12.62	29.43	55.44
S1	2.13	11.88	28.73	57.26
S2	4.5	14.54	26.34	54.62
S3	3.31	19.35	23.29	54.05
T1	4.34	28.45	24.83	42.38
T2	4.38	15.78	23.85	55.99
T3	2.51	13.86	25.98	57.65
U1	2.05	14.52	23.89	59.54
U2	2.59	13.56	21.24	62.61
U3	3.84	13.73	30.63	51.8
U4	2.99	15.87	23.35	57.79
GV1	7.3	34.21	36.26	22.21
GV2	5.45	29.36	31.21	33.96
GV3	2.97	23.16	24.51	49.35
GV4	3.1	24.59	25.91	46.38
GV5	4.98	26.47	28.1	40.51
V1	4.79	15.55	28.94	50.72
V2	3.78	12.98	29.13	54.11
V3	4.1	13.83	28.66	53.41
W1	3.93	13.71	27.38	54.98
W2	3.95	21.23	26.59	48.23
Average	**3.32**	**16.95**	**27.50**	**52.21**
Standard deviation (σ)	**1.10**	**5.7**	**3.81**	**7.7**

Table 6.2: Proximate analysis for coal samples

6.5 Volatile matter

Volatile matter percentage varies from 15.98-36.36 in coal samples of the study area. The average value of volatile matter percentage is 27.50% in coal samples (Tables 6.1 and 6.2). Volatile matter percentages also fluctuated, crossing the fixed carbon for the GV1 coal sample. The standard deviation (σ) and standard error of the mean for volatile matter are 3.81 and 0.50 for coal samples.

6.6 Fixed carbon

Fixed carbon percentage varies from 33.96-62.61 in coal samples of the study area. The average value of fixed carbon percentage is 52.11% in coal samples (Tables 6.1 and 6.2). The standard deviation (σ) and standard error of the mean for fixed carbon are 7.77 and 1.03 for coal samples.

6.7 Gross calorific value of coal

Calorific value is the most important property of coal. It is a type of measure obtained by burning coal. It is the most important parameter for the assessment of the quality of coal because the use of coal is based on the available heat (energy) that is produced from it (Kumari et al. 2019).

Gross calorific value (GCV) varies from 3438 to 6743 Kcal/Kg in coal samples of the study area. The average content of GCV is 5726.5 Kcal/Kg in coal samples. So, according to the average content of GCV, the coal samples belonged to "G-6" grade coal (Ministry of Coal, GOI 2014). The GCV value is not static in coal samples. The variations in GCV can be seen in graphical representation (Figs. 6.6 and 6.7). The standard deviation (σ) and standard error of the mean for GCV are 5.7 and 0.77 for coal samples.

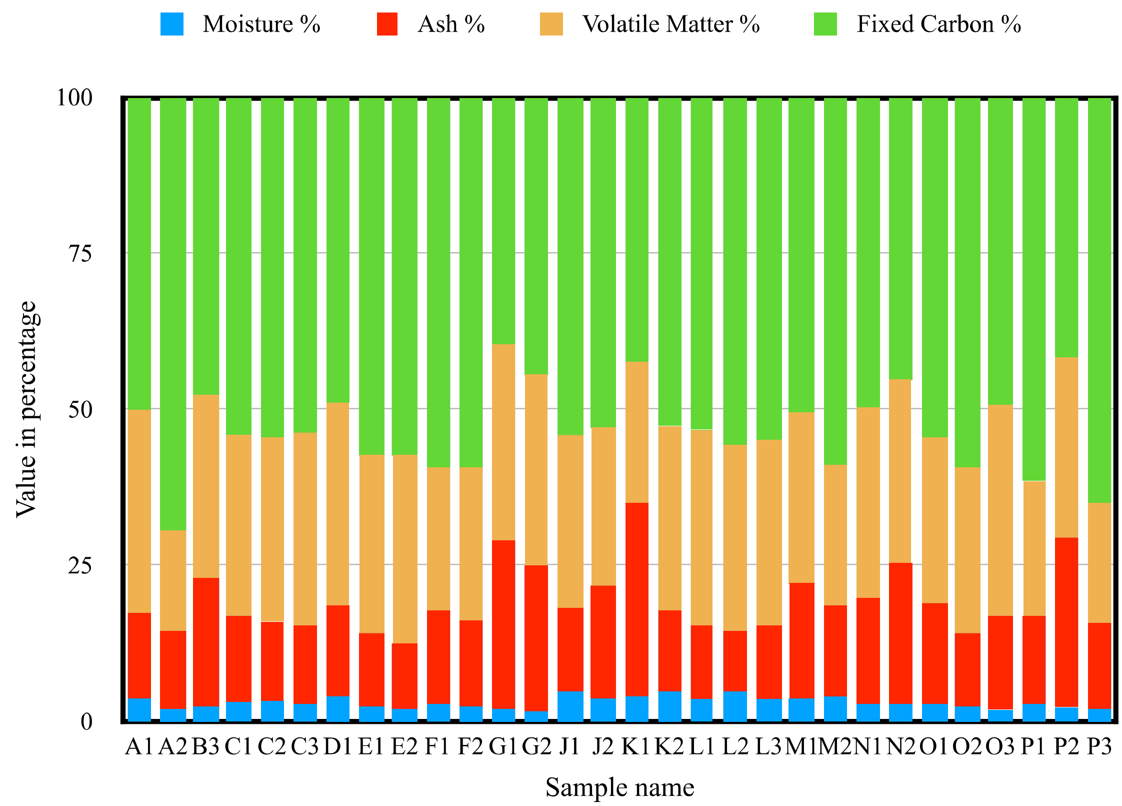


Fig. 6.4: Proximate analysis of coal samples for table 6.1

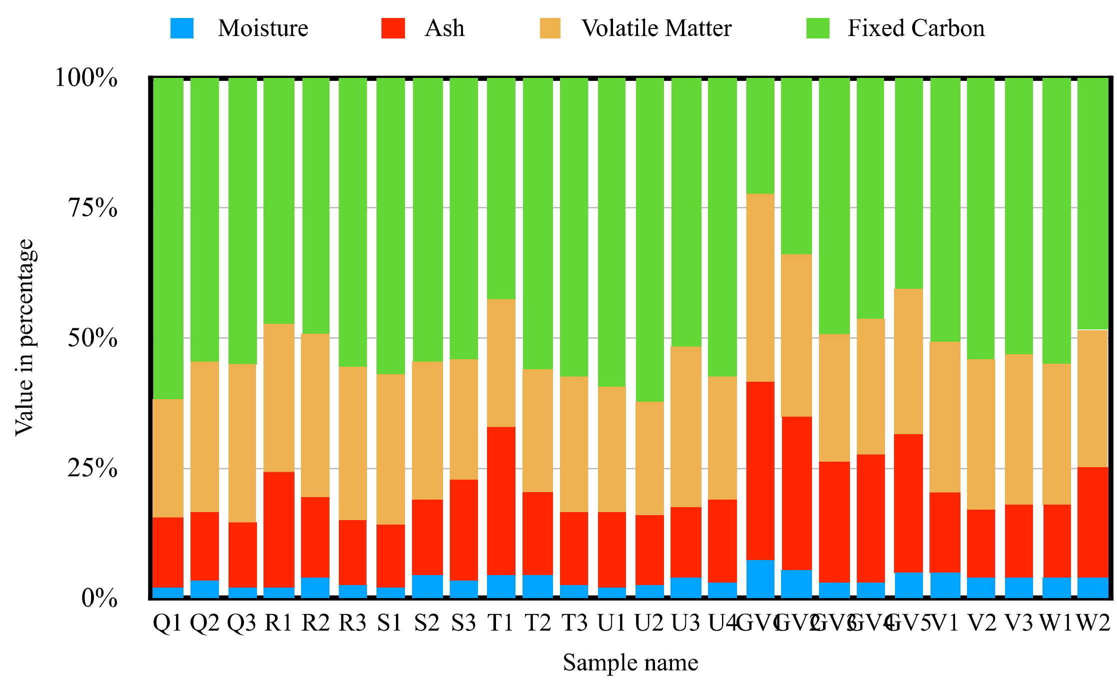


Fig. 6.5: Proximate analysis of coal samples for table 6.2

6.8 Distribution of proximate constituents

In the present study, coal samples were drawn from all the working sections of the Dhanpuri opencast mine of the Sohagpur coalfield and were subjected to proximate

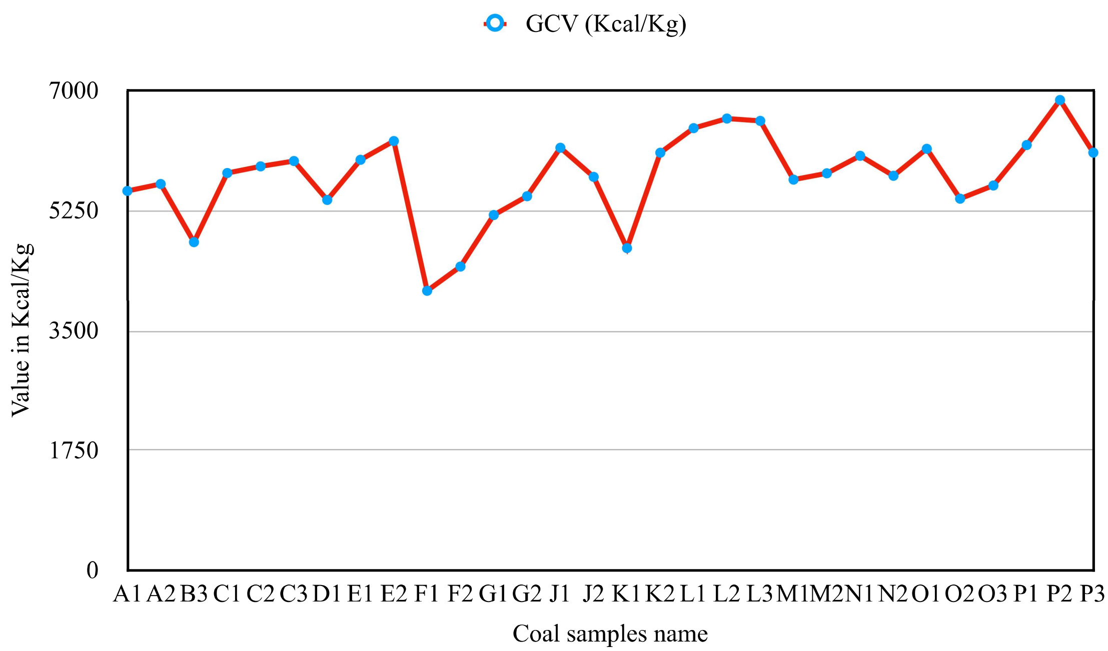


Fig. 6.6: Gross calorific value for Dhanpuri OCP coal samples.

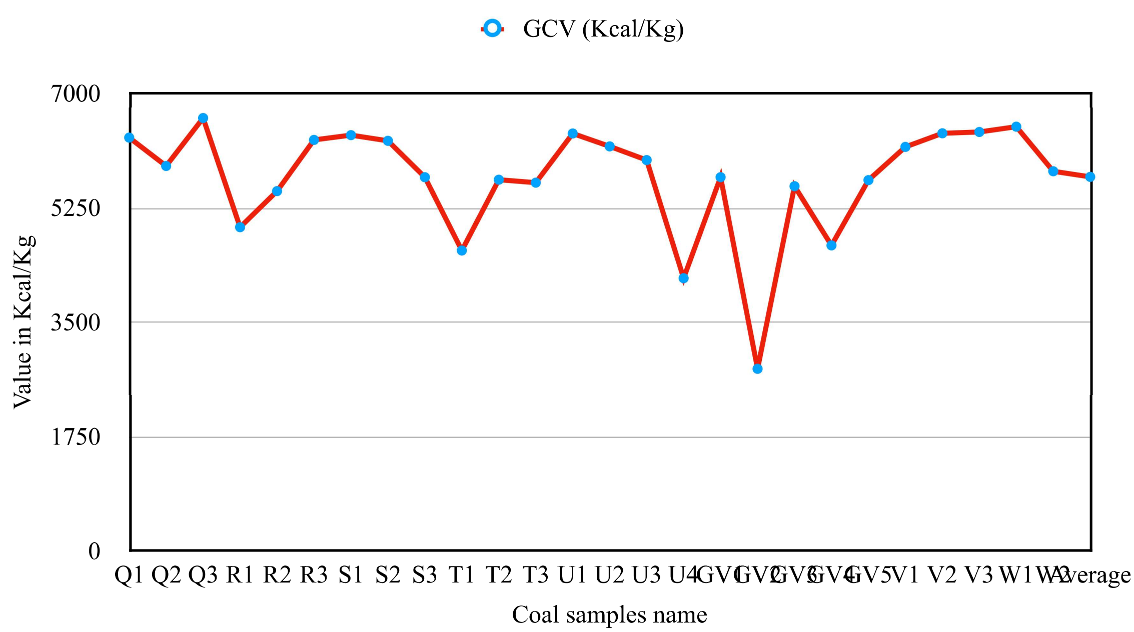


Fig. 6.7: Gross calorific value for Dhanpuri OCP coal samples.

Sample Name	GCV (Kcal/Kg)	Sample Name	GCV (Kcal/Kg)
A-1	5537	Q1	6326
A-2	5638	Q2	5893
B3	4791	Q3	6625
C1	5798	R1	4958
C2	5895	R2	5509
C3	5973	R3	6291
D1	5406	S1	6364
E1	5991	S2	6277
E2	6264	S3	5721
F1	4082	T1	4602
F2	4435	T2	5683
G1	5186	T3	5638
G2	5460	U1	6389
J1	6166	U2	6192
J2	5742	U3	5983
K1	4704	U4	4179
K2	6094	GV1	5722
L1	6452	GV2	2795
L2	6592	GV3	5584
L3	6558	GV4	4680
M1	5702	GV5	5677
M2	5794	V1	6184
N1	6049	V2	6392
N2	5758	V3	6412
O1	6151	W1	6493
O2	5424	W2	5812
O3	5616	**Average**	**5726.5**
P1	6206	**Standard deviation (σ)**	**741.9**
P2	6862		
P3	6095		

Table 6.3: Gross calorific value for Dhanpuri OCP coal samples.

analysis. This made it possible to know the variation in the distribution of proximate constituents in the coal mines. Significance, interpretation and utilization are further discussed in chapter nine.

6.9 Ultimate analysis

The ultimate analysis or major elemental analysis is done in terms of carbon, hydrogen, nitrogen, oxygen and sulphur percentage in coal samples. Their quantitative information is vital and elements like carbon and hydrogen are helpful in rank determination as well as in the characterization of coal for coking, gasification and liquefaction (hydrogenation) processes (Ozer et al. 2017). The elements nitrogen and sulphur are potential pollutants in the environment (Greaver et al. 2012).

The carbon percentage varies from 51.41-75.36% in coal samples of the study area. The average content of carbon is 63.05% in coal samples. The standard deviation (σ) and standard error of the mean for carbon are 6.24 and 1.13 for coal samples. Hydrogen varies from 3.13-5.98% in coal samples of the study area. The average content of hydrogen is 4.37% in coal samples. The standard deviation (σ) and standard error of the mean for hydrogen are 0.65 and 0.11 for coal samples. Nitrogen varies from 0.414-0.856% in coal samples of the study area. The average content of nitrogen is 0.578% in coal samples. The standard deviation (σ) and standard error of the mean for nitrogen are 0.10 and 0.01 for coal samples. Sulphur varies from 0.56-1.87% in coal samples of the study area. The average content of sulphur is 1.38% in coal samples. The standard deviation (σ) and standard error of the mean for sulphur are 0.35 and 0.06 for coal samples. Oxygen varies from 18.22-42.13% in coal samples, and the average content of oxygen is 31.14% in coal samples of the study area (Fig. 6.8 and Table 6.4), however, oxygen was calculated by formula as follows:

Sample	Carbon	Hydrogen	Nitrogen	Oxygen	Sulphur
A1	64.11	4.45	0.596	28.083	1.763
A2	63.38	4.79	0.657	30.07	1.1
B3	59.13	4.1	0.576	34.98	1.21
C1	65.36	4.27	0.545	29.26	0.56
C2	66.1	5.1	0.534	27.26	1
C3	67.09	4.47	0.576	26.88	0.981
D1	58.69	4.08	0.734	35.695	0.801
E1	68.67	4.22	0.512	26.28	1.3
E2	69.53	5.07	0.55	24.19	1.6
F1	55.75	3.67	0.459	39.69	1.43
F2	59.3	3.65	0.552	35.94	1.55
G1	62.03	4.45	0.563	31.99	0.96
G2	63.36	5.3	0.632	30.37	1.438
J1	69.78	4.3	0.759	24.58	1.58
J2	55.96	3.69	0.856	38.71	1.76
K1	59.18	4.3	0.596	34.56	1.36
K2	66.36	4.13	0.593	27.94	0.968
L1	71.36	4.6	0.636	22.84	1.568
L2	75.36	3.65	0.563	19.54	1.879
L3	72.36	4.36	0.456	21.87	0.947
M1	59.36	3.13	0.753	36.18	1.568
M2	63.36	3.56	0.512	31.69	1.874
N1	58.36	5.36	0.458	35.13	1.68
N2	54.36	3.98	0.57	40.43	1.659
O1	59.36	4.97	0.678	34.192	1.8
O2	55.36	5.98	0.512	37.46	1.684
O3	58.36	3.54	0.499	37.03	1.57
P1	63.36	4.1	0.589	31.08	0.98
P2	51.41	5.36	0.435	42.13	1.658
P3	75.36	4.7	0.414	18.22	1.3
Average	**63.05**	**4.37**	**0.578**	**31.14**	**1.384**
Standard deviation (σ)	**6.24**	**0.65**	**0.10**	**6.33**	**0.35**

Table 6.4: Tabular presentation of ultimate analysis for coal samples in percentage

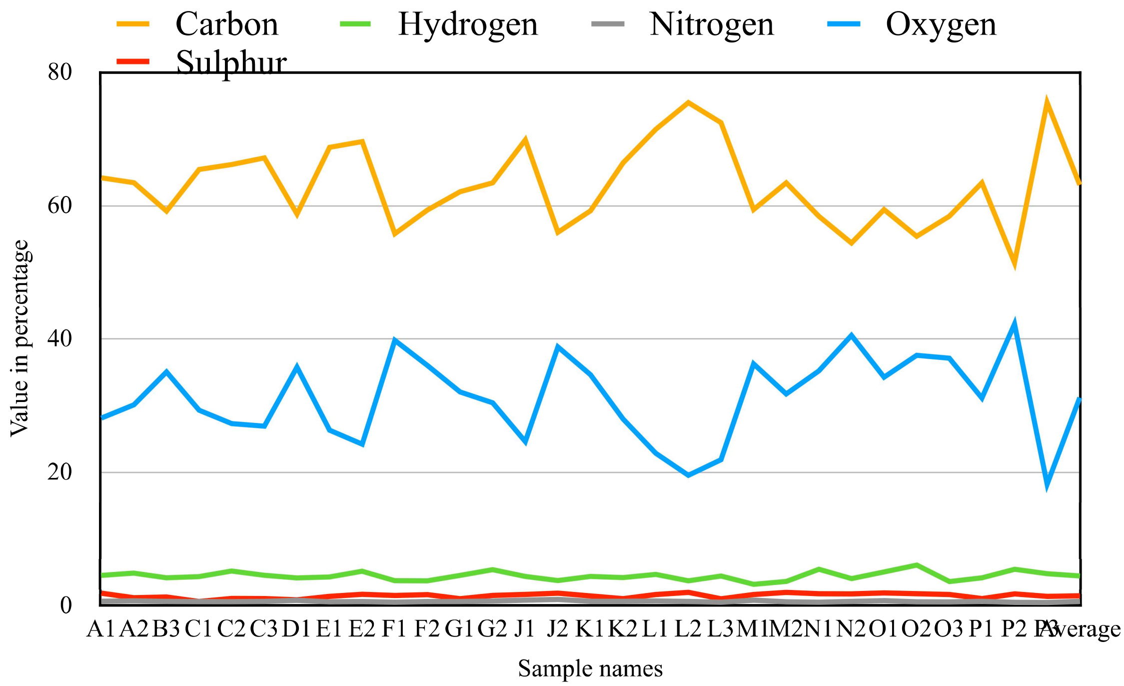


Fig. 6.8: Ultimate analysis of coal samples

Oxygen= 100- (Carbon%+Hydrogen%+Nitrogen%+Sulphur %)

The standard deviation (σ) and standard error of the mean for oxygen are 6.33 and 1.15 for coal samples.

6.10 Trace element

There has been growing interest in the study of the concentration and distribution of trace elements in coal in the last few decades (Finkelman 1999). The information is vital from an economic as well as an environmental point of view. In coal, the metals get accumulated at various stages. There are three stages of ore processes in coal-syngenetic, diagenetic and epigenetic (Danchev and Strelyanov 1979; Kler et al. 1988). Many studies are going on regarding the concentration and distribution of trace elements in coal in the last few decades. Trace elements also come along with all these three processes in the coal formation as said above. Several elements have been analyzed such as chromium (Cr), manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), molybdenum (Mo), cadmium (Cd), hafnium (Hf), and lead (Pb). The average concentration of Cr is 78,910 ppb, Mn is 55,320 ppb, Co is 14,420 ppb, Ni is 19,420 ppb, Cu is 7,820 ppb, Zn is 26,020 ppb, As is 8,000 ppb, Mo is 11,960 ppb, Cd is 70 ppb, Hf is 1,060 ppb, and Pb is 16,920 ppb (Table 6.5). It was found in coal samples, the highest level of trace elements was chromium, and the lowest was cadmium.

Trace elements in coal samples of the study area are also compared with the World Clarke Hard Coal (WCHC) average in table 6.7 which depicts that some trace elements are higher in coal samples of the study area. Chromium is very much higher as compared, along with cobalt, nickel, molybdenum and lead. Identification of minerals is also important, which can be related to the trace elements concentration in samples. These trace elements are mostly associated with the inorganic content in coal which can be unveiled after mineral identification in coal samples (Singh et al. 2015).

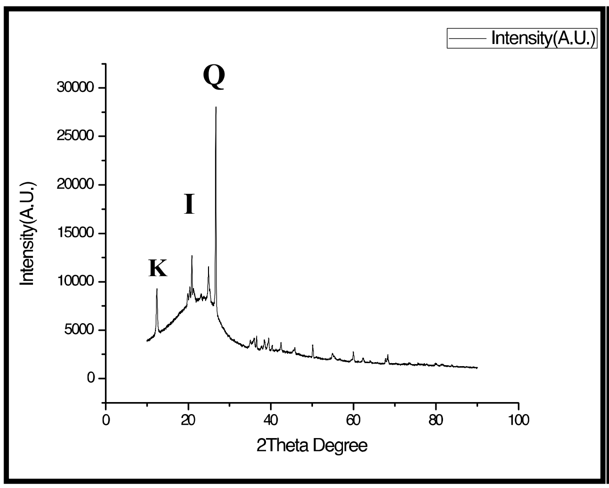
6.11 X-ray diffraction study

X-ray diffraction (XRD) can help to identify minerals in coal (Ward 2016). Some 200 minerals have been observed in coal (Finkelman et al. 1981). The minerals in these coal samples were identified from XRD spectra and compared its ‘d’ values as per Lindholm (1987). The minerals identified in coal samples were included kaolinite, illite, monazite, andalusite, quartz, hematite, gypsum, and graphite in the study area. Many mineral groups were identified in coal samples. Kaolinite and illite were the major clay minerals, while hematite was an iron-containing mineral. Andalusite is an alumina-silicate

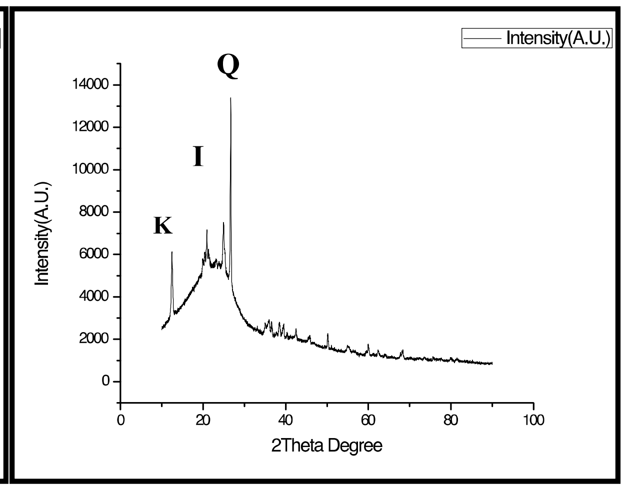
Elements	Cr	Mn	Co	Ni	Cu	Zn	As	Mo	Cd	Hf	Pb
Concentration (in ppb)	78910	55320	14420	19420	7820	26020	8000	11960	70	1060	16920

Table 6.5 : Trace elements concentration in coal samples

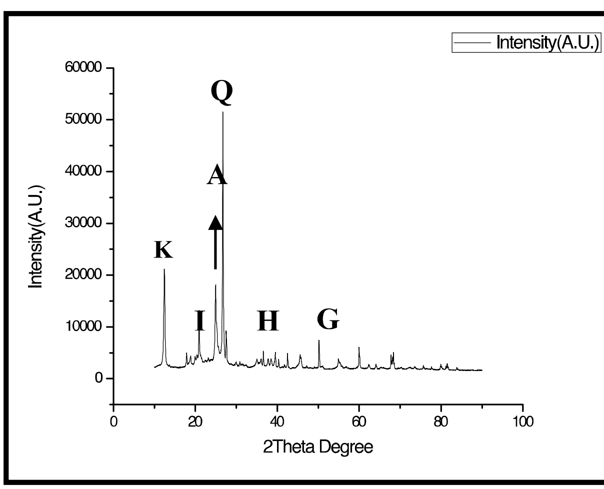
mineral. Gypsum represents the calcium sulphate phase in coal samples (Fig. 6.9). It can be seen that silicate minerals were identified in samples from XRD peaks as said earlier in the introduction chapter (chapter one). It is also needed to support the mineralogical content in coal samples by further analysis.



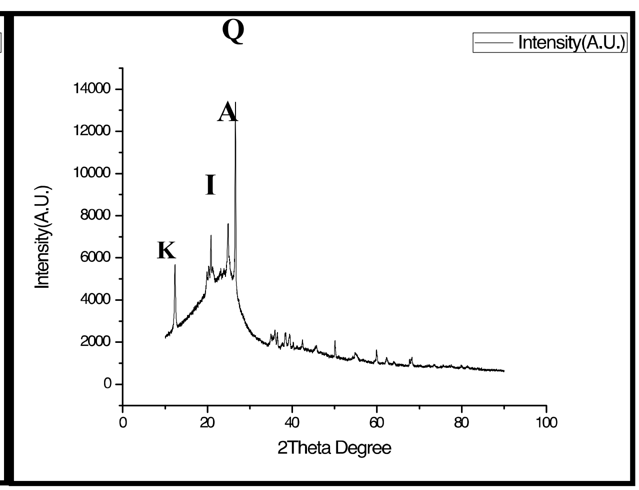
Sample No. A1



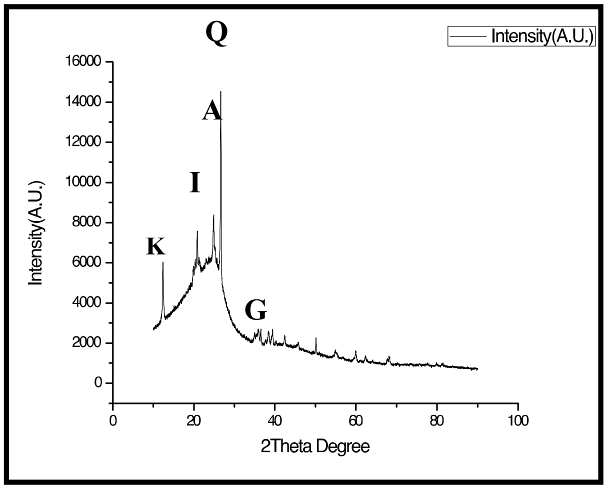
Sample No. A2



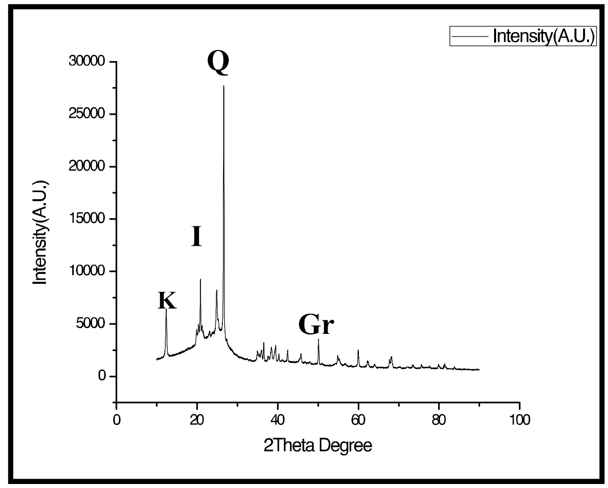
Sample No. B1



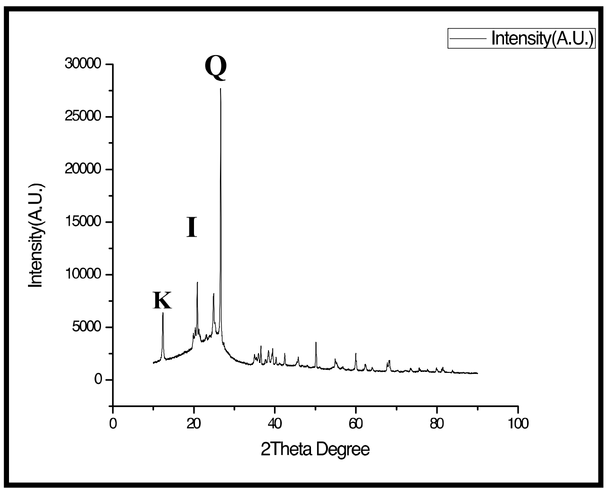
Sample No. C1



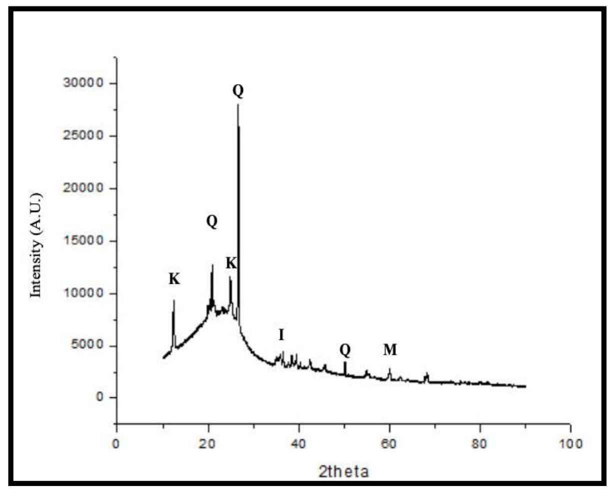
Sample No. F1



Sample No. F2



Sample No. K1

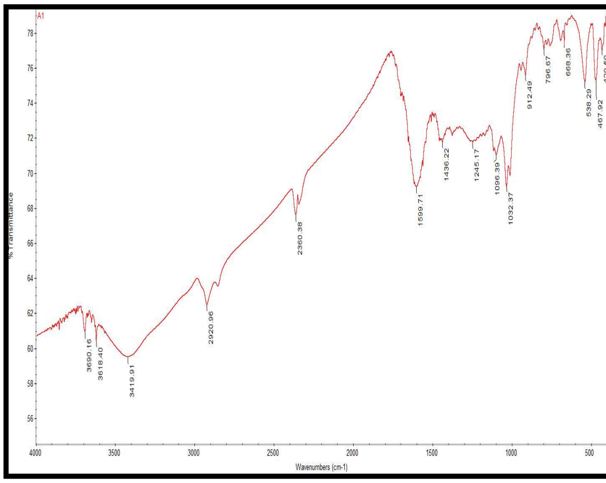


Sample No. G2

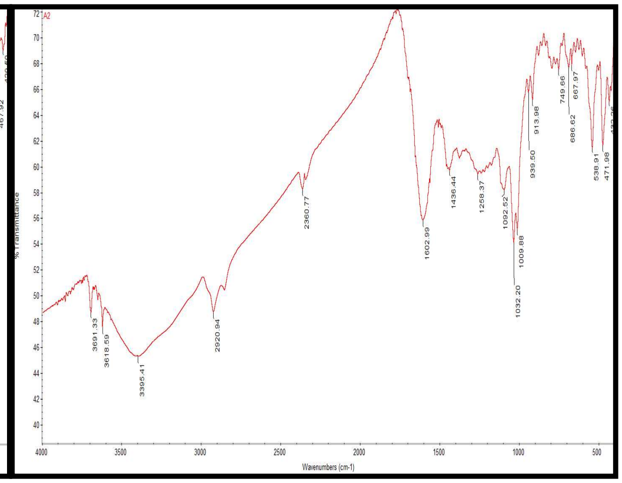
Fig. 6.9: X-ray diffraction patterns of coal samples on intensity and 2 theta degree scale; K= Kaolinite; I= Illite; A= Andalusite; Q= Quartz; H= Hematite; G= Gypsum; Gr= Graphite; M= Monazite.

6.12 Fourier transform infrared (FTIR) spectroscopy

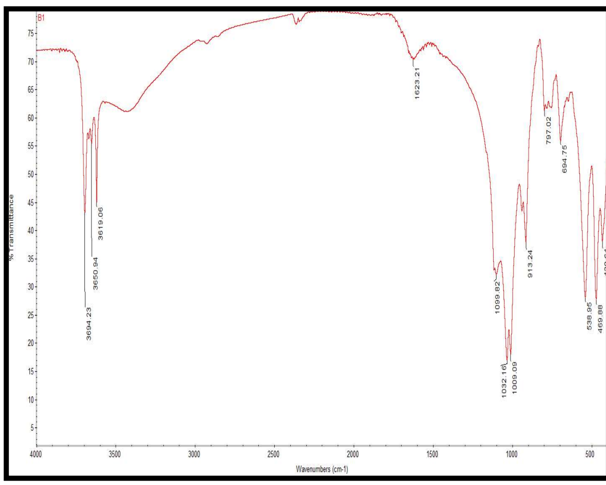
FTIR spectroscopy was employed to identify the content and position of the functional groups in coal. Quantitative analysis of the various functional groups of coal was conducted by measuring the FTIR spectra. It was also used to detect the presence of minerals (Balachandran2014). By comparing the result of frequency after the literature survey, FTIR showed the presence of strong aliphatic absorption (v-CH, $-CH_2$ and $-CH_3$)



Sample No. A1



Sample No. A2



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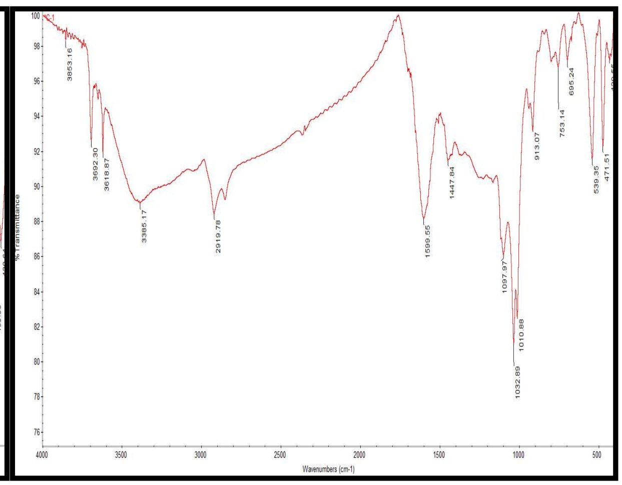
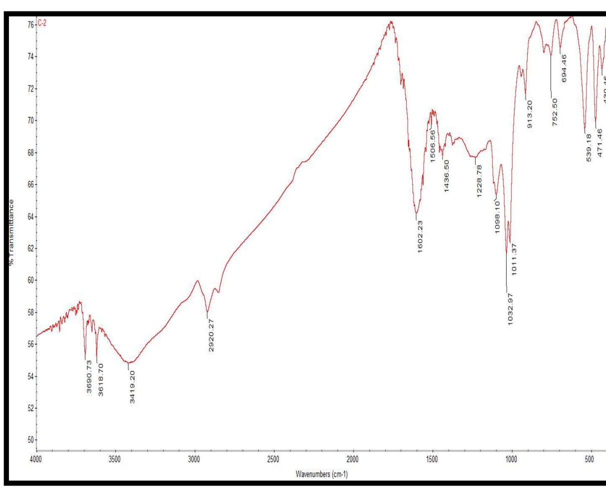
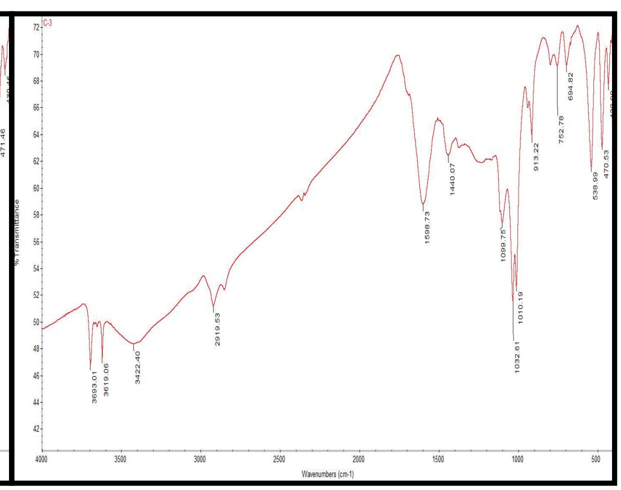


Sample No. C1

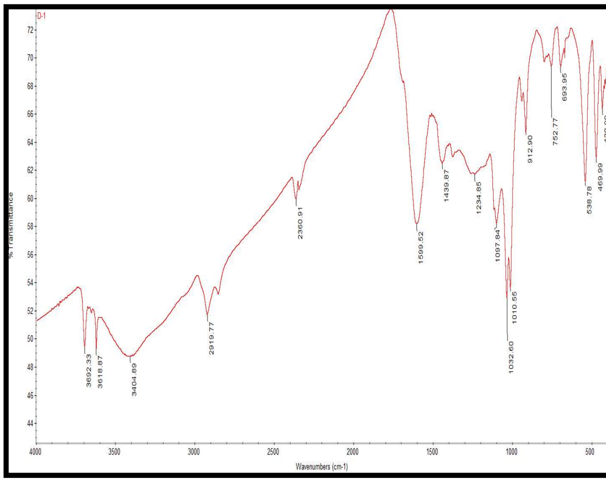


Sample No. C2

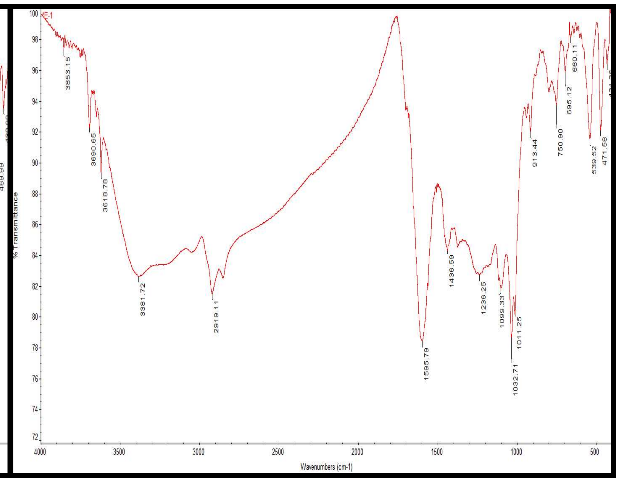


Sample No. C3

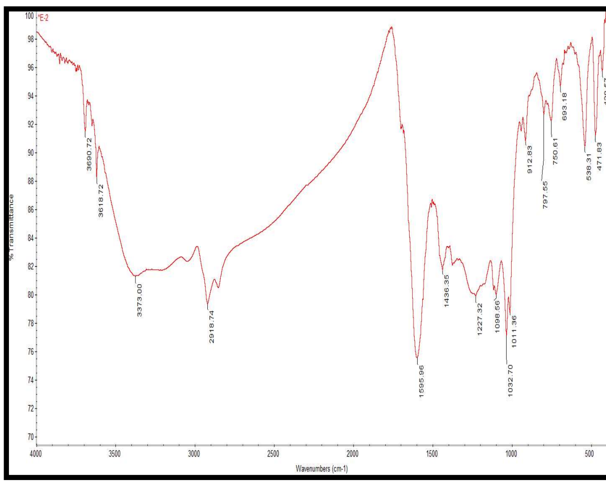
Fig. 6.10: Graphical representation of FTIR for coal samples with band region



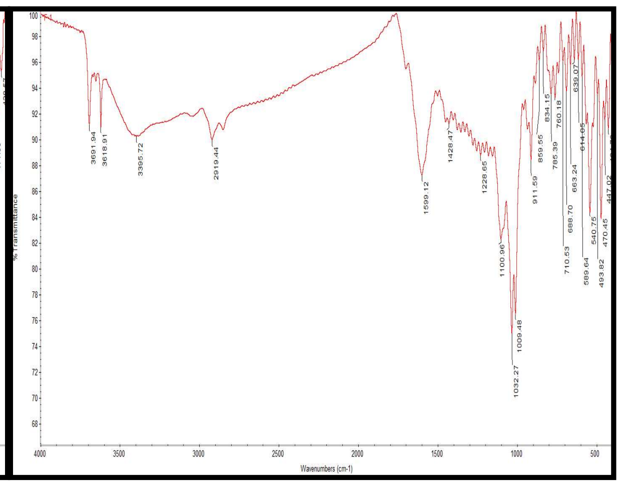
Sample No. D1



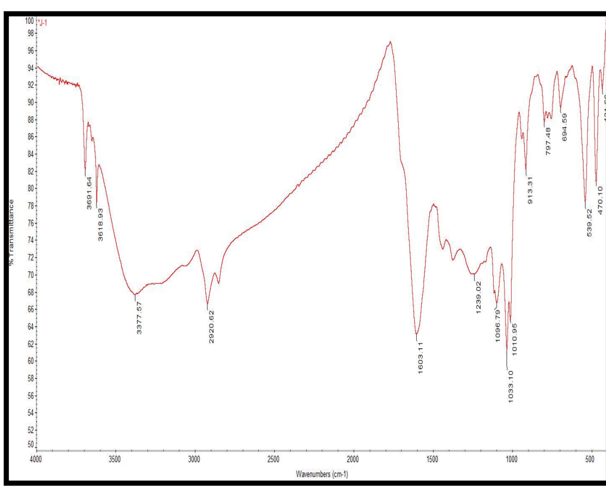
Sample No. E1



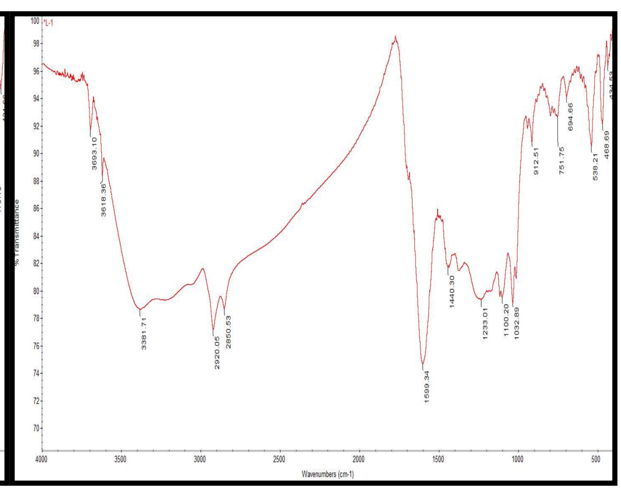
Sample No. E2



Sample No. F1



Sample No. J1



Sample No. L1

Fig. 6.11: Graphical representation of FTIR for coal samples with band region

Band Region	Functional group assignment
3600-3200	-OH stretching vibration
3080-3035	Aromatic nucleus CH stretching vibration
2975-2955	Aliphatic CH_3 asymmetric stretching vibration
2925-2919	Aliphatic CH_2 asymmetric stretching vibration
2863	Aliphatic CH_3 symmetric stretching vibration
2848	Aliphatic CH_2 symmetric stretching vibration
2400-2000	Inorganic Carbonyl Compounds
1745-1730	Aliphatic (grease, acid, ketone, aldehyde) (C=O)
1721-1695	Aromatic (carbonyl/carboxyl groups) (C=O)
1650-1630	C=O, highly conjugated
1615-1585	Aromatic nucleus (C=C)
1590-1560	Carboxylic group in salt from COO
1435	Aliphatic CH_2 and CH_3 bending vibration
1380	Symmetric deformation $-CH_2-$ (bending)
1097	Si-O-Si asymmetric stretching vibration
1032	Si-O Stretching of clay mineral
794	Si-O Symmetric
880-860	Aromatic nucleus (CH), one adjacent H deformation
776-730	Aromatic nucleus (CH), three to four adjacent H
463	Amorphous silica Si-O-Si band

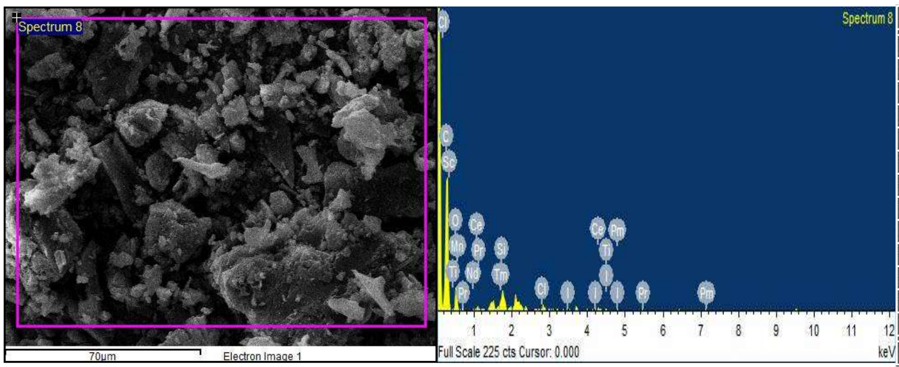
Table 6.6: Band assignments derived from FTIR spectra (D. Wu et al., 2012; Davis et al., 1981; Painter et al., 1985; Katara et al., 2013; Hlavay et al., 1978; Coates, 1977; Farmer, 1974;Clarence, 1974; Russell, 1987)

in coal samples. Other organic groups including -OH, C=C, C-O, C-OH, O=C=O, and C-O-C were also identified in coal samples. The peaks in FTIR spectra of coal between 1100 and 400 cm^{-1} were of clay minerals such as quartz, kaolinite, illite and montmorillonite groups. The absorption band in 3454 wave number (cm^{-1}) showed the presence of an OH group stretching vibrations, which were the hydroxyl stretching of inner surface hydroxyl of kaolinite respectively. The band at 1632 cm^{-1} was attributed to O–H stretching and bending hydroxyl that might be from the kaolinite mineral of coal (Cheng et al. 2010). The absorption band of 2923 and 1622 wave number(cm^{-1}) showed the presence of organic carbon and organic matter in coal samples of the study area (Figs. 6.10, 6.11 and Table 6.6). Due to the heterogeneous nature of coal, it also contains valuable elements along with major elements in coal.

6.13 Scanning electron microscopic with elemental distribution concentration (SEM with EDX)

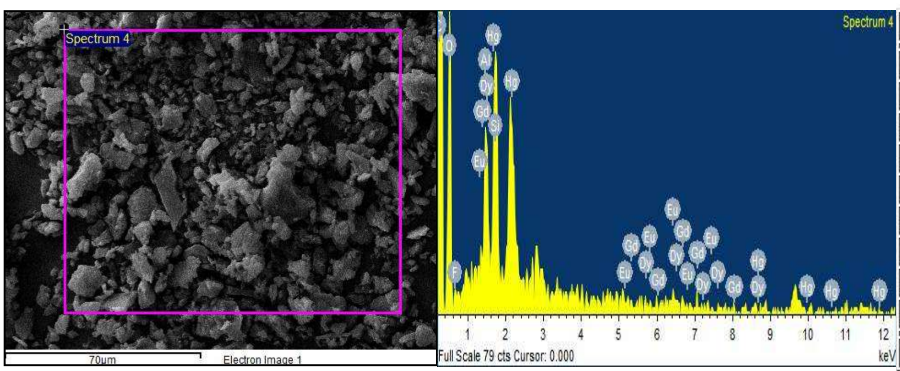
SEM micrograph images of the collected coal samples were helped in the comprehensive analysis of micro-morphology of solid surfaces and in examining the fissure, fracture or internal structure of materials (Nie et al. 2015). SEM-EDX observed that the surface morphology of coal samples were non-uniform (Fig. 6.12). The micrograph exhibit a homogeneously distributed network of minerals in form of small crystallites. Both luminous and non-luminous structures can be witnessed in the matrix. It reveals the presence of minerals encapsulated in a carbon matrix (Manoj 2016). In the analysis done by scanning electron microscope with the help of the energy dispersive x-ray (SEM with EDX), we can see the elemental distribution in coal samples.

The EDX analysis illustrates that the coal samples of the study area exhibited a wide range of elemental composition containing carbon (C), oxygen (O), silicon (Si), aluminium (Al) as the major constituents. While other elements were present in trace amount in various samples collected from the study area. The elemental composition in weight and atomic percentage (%) of Sohagpur coalfield of carbon (C) varies from 43.92 to 70.66% ($\bar{x}$ = 61.97%) and 56.71 to 87.10% ($\bar{x}$ = 76.22%) respectively, oxygen (O) varies from 10.08 to 24.60% ($\bar{x}$ = 21.88%) and 9.95 to 34.05% ($\bar{x}$ = 20.17%) respectively, aluminum (Al) varies from 1.05 to 5.80% ($\bar{x}$ = 3.48%) and 0.52 to 20.23% ($\bar{x}$ = 8.11%) respectively, silica (Si) varies from 1.57 to 8.13% ($\bar{x}$ = 3.99%) and 0.88 to 27.26% ($\bar{x}$ = 7.39%) respectively, chlorine (Cl) varies from 0.0 to 0.37% ($\bar{x}$ = 0.18%) and 0.00 to 0.14% ($\bar{x}$ = 0.07%) respectively, scandium (Sc) varies from 0.00 to 0.25% ($\bar{x}$ = 0.12%) and 0.00 to 0.08% ($\bar{x}$ = 0.04%) respectively, manganese (Mn) varies from 0.23 to 0.27% ($\bar{x}$ = 0.25%) and 0.07% ($\bar{x}$ = 0.07%) respectively, cerium (Ce) varies



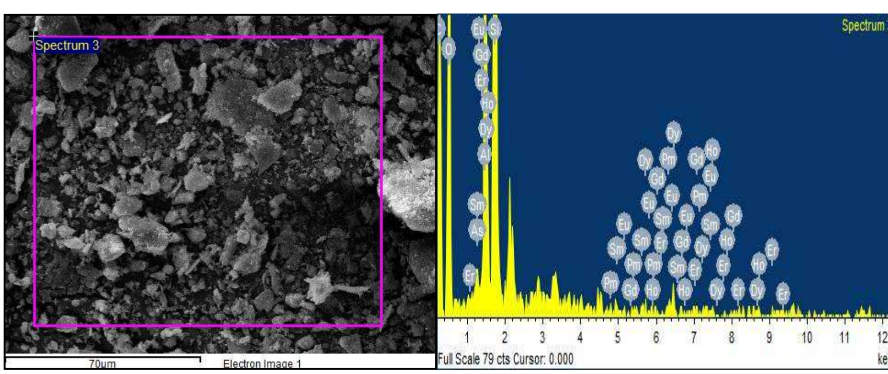
Element	Weight%	Atomic%
C K	66.73	76.98
O K	24.32	21.06
Si K	2.15	1.06
Cl K	0.37	0.14
Sc K	0.25	0.08
Ti K	0.15	0.04
Mn K	0.27	0.07
I L	1.69	0.18
Ce L	0.60	0.06
Pr L	0.85	0.08
Nd L	0.82	0.08
Pm L	1.26	0.12
Tm L	0.56	0.05
Totals	100.00	

Sample A1



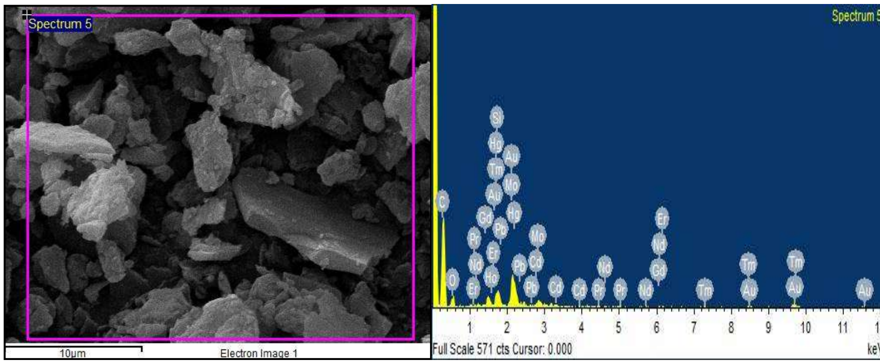
Element	Weight%	Atomic%
C K	70.66	77.65
O K	24.60	20.29
F K	0.84	0.58
Al K	1.05	0.52
Si K	1.87	0.88
Eu L	0.21	0.02
Gd L	0.23	0.02
Dy L	0.30	0.02
Hg M	0.24	0.02
Totals	100.00	

Sample A2



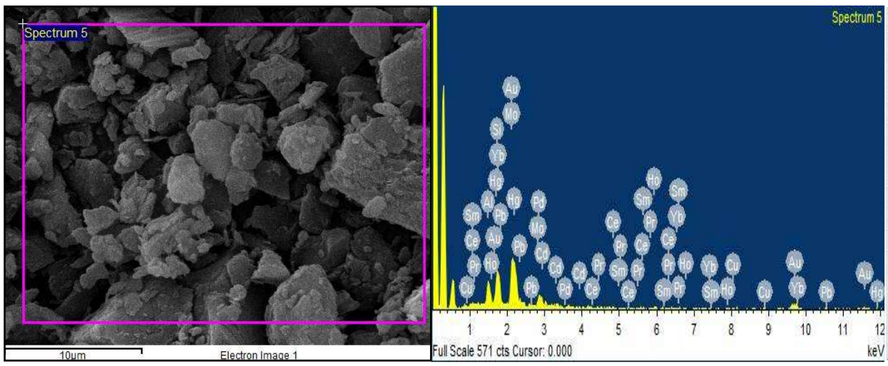
Element	Weight%	Atomic%
C K	43.92	56.71
O K	36.14	35.04
Al K	5.30	3.04
Si K	8.04	4.44
As L	1.06	0.22
Pm L	0.80	0.08
Sm L	0.68	0.07
Eu L	0.85	0.09
Gd L	0.98	0.10
Dy L	0.63	0.06
Ho L	0.91	0.09
Er L	0.69	0.06
Totals	100.00	

Sample B1



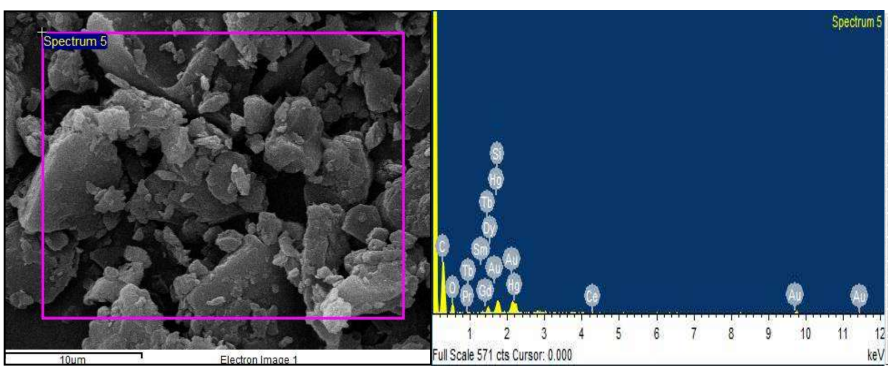
Element	Weight%	Atomic%
C K	66.22	87.10
O K	10.08	9.95
Si K	1.57	0.88
Mo L	2.51	0.41
Cd L	0.41	0.06
Pr L	0.43	0.05
Nd L	0.69	0.08
Gd L	0.38	0.04
Ho L	0.27	0.03
Er L	0.19	0.02
Tm L	0.77	0.07
Au M	15.25	1.22
Hg M	0.16	0.01
Pb M	1.08	0.08
Totals	100.00	

Sample C1



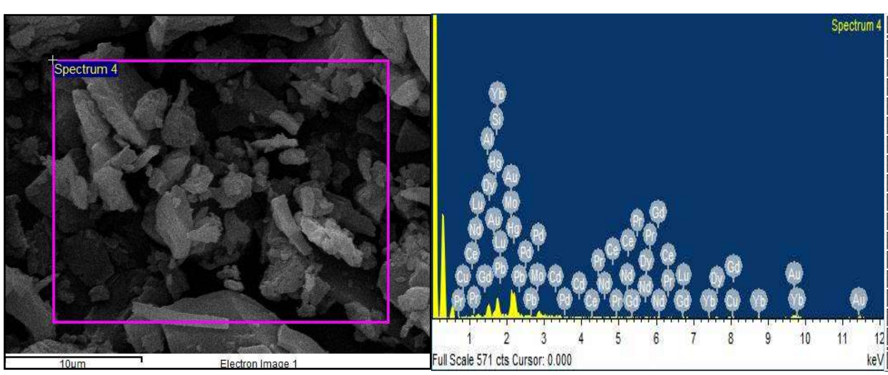
Element	Weight%	Atomic%
Al K	5.80	20.23
Si K	8.13	27.26
Cu K	0.62	0.92
Mo L	8.65	8.48
Pd L	12.90	11.41
Cd L	0.93	0.78
Ce L	1.28	0.86
Pr L	1.51	1.01
Sm L	1.38	0.87
Ho L	1.69	0.96
Yb L	0.13	0.07
Au M	51.91	24.82
Hg M	1.28	0.60
Pb M	3.78	1.72
Totals	100.00	

Sample C2



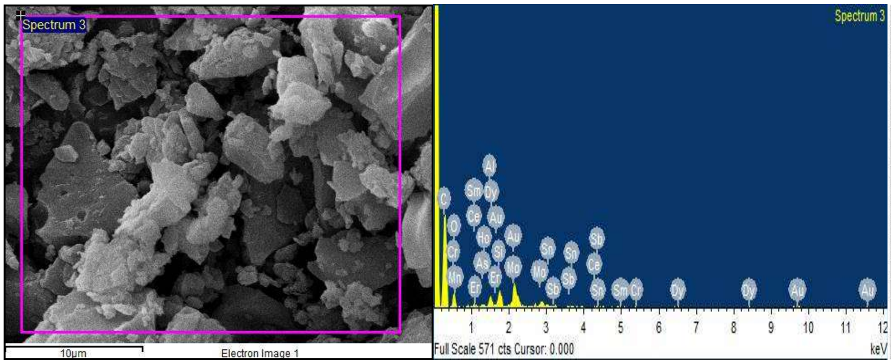
Element	Weight%	Atomic%
C K	62.16	78.34
O K	20.14	19.06
Si K	2.41	1.30
Ce L	0.73	0.08
Pr L	1.11	0.12
Pm L	0.49	0.05
Sm L	0.60	0.06
Gd L	0.49	0.05
Tb L	1.43	0.14
Dy L	0.28	0.03
Au M	8.80	0.68
Hg M	1.35	0.10
Totals	100.00	

Sample D1



Element	Weight%	Atomic%
Al K	4.15	16.14
Si K	6.00	22.40
Cu K	2.38	3.94
Mo L	4.41	4.83
Pd L	10.58	10.44
Cd L	3.11	2.90
Ce L	1.42	1.06
Pr L	1.65	1.23
Nd L	3.30	2.40
Gd L	2.20	1.47
Dy L	0.20	0.13
Yb L	2.36	1.43
Lu L	10.37	6.22
Au M	43.95	23.42
Hg M	0.68	0.36
Pb M	3.24	1.64
Totals	100.00	

Sample G2



Element	Weight%	Atomic%
C K	62.12	80.67
O K	16.03	15.63
Al K	1.12	0.65
Si K	1.75	0.97
Cr K	0.19	0.06
Mn K	0.23	0.07
As L	1.28	0.27
Mo L	2.80	0.46
Sn L	0.27	0.04
Sb L	0.29	0.04
Ce L	0.43	0.05
Sm L	0.87	0.09
Dy L	0.86	0.08
Ho L	0.52	0.05
Er L	0.13	0.01
Au M	11.11	0.88
Totals	100.00	

Sample O1

Fig. 6.12: Elemental distribution in coal samples by SEM with EDX analysis

from 0.43 to 1.42% ($\bar{x}$ = 0.89%) and 0.05 to 1.06% ($\bar{x}$ = 0.42%) respectively, samarium (Sm) varies from 0.39 to 1.94% ($\bar{x}$ = 1.17%) and 0.04 to 0.24% ($\bar{x}$ = 0.14%) respectively, neodymium (Nd) varies from 0.69 to 3.30% ($\bar{x}$ = 1.60%) and 0.08 to 2.40% ($\bar{x}$ = 0.85%) respectively, promethium varies from 0.49 to 1.26 ($\bar{x}$ = 0.85%) and 0.05 to 0.12% ($\bar{x}$ = 0.08%) respectively.

In figure 6.14 is showing the elemental distribution in the coal samples for different spectrums. Atomic percentage and weight percentage were determined by EDX in coal samples of the study area. With the help of the coal sample's microphotograph images, it depicts coal particles of various sizes. The minerals matter is not clear from the images, it (mineral matter) cannot be seen on coal particles, and probably it is embedded inside the bulk of the carbonaceous matter. It is also unclear for REEs, whether it is associated with organic or inorganic matter. Coal particles were rough, irregular and angular in shape and size. Uneven textures were also found on the coal particles in the images. This is required for leaching because the surface area is an important phenomenon so that chemicals can react with organic and inorganic matter. The higher the surface area, higher will be reactivity of chemicals with the materials in coal samples (Buckwalter et al. 1982).

Characterization of surface morphology of coal samples will also help in interpretation after leaching experiments. It (characterization of surface morphology) can also help in the fabrication, plotting and designing of experimental work in future studies. Energy Dispersive X-ray (EDX) showed the presences of the rare earth elements in coal samples of the study area. It can also be seen in the atomic percentage and weight percentage of sample wise (Fig. 6.14). For confirmation, the coal samples were analyzed by ICP-MS for REEs and trace elements concentration which will be further discussed in the next chapter.

Elements	WCHC	Mean
Cr	17 ± 1	78.91
Mn	71 ± 5	55.32
Co	6.0 ± 0.2	14.42
Ni	17 ± 1	19.42
Cu	16 ± 1	7.8
Zn	28 ± 2	26.02
As	9.0 ± 0.7	8
Mo	2.1 ± 0.1	11.96
Cd	0.20 ± 0.04	0.07
Hf	1.2 ± 0.1	1.06
Pb	9.0±0.7	16.92

Table 6.7: Mean of trace elements in Dhanpuri coal and it’s comparison with the World Clark Hard Coal (WCHC) average