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RESEARCH ARTICLE

Study on Quality and Elemental Composition of Gazestan Coal Mine, Takhar Province, Afghanistan

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ABSTRACT

Coal is one of the world's main energy resources and has an important role in electricity generation and industrial activities. The chemical and elemental properties of coal are of great importance to its quality and potential uses. In this study, the quality indices and elemental analysis of coal from the Gazestan coal mine in Takhar province in Afghanistan were performed. At approximately 120, 160 and 200 m from the mine entrance, three coal samples were collected at different positions in the coal seam along the second mining gallery. The elemental composition was determined by the XRF analysis and the coal quality indices were evaluated using thermal treatment experiments. The results showed that the sulfur concentrations were in the range of 263-872 ppm with the highest concentration in sample GZ-1. Sample GZ-3 had a calcium concentration of 8.68%, which was much higher than that in other samples. Ash content was found to be between 29.77% and 69.90% whereas volatile matter was found to be between 30.06% and 70.22%. The maximum ash content was observed in sample GZ-2 and the minimum in GZ-3. The results also showed that with the increase in the depth of mining there was a decrease in ash yield and sulfur concentration, along with an increase in calcium content. Such changes can reduce the environmental impacts associated with burning coal. The coal from estimated depth of 200 m was classified as bituminous coal based on quality indices obtained and can be suitable for industrial applications especially in cement manufacturing.

KEYWORDS

Coal quality, elemental composition, Gazestan coal mine, thermal treatment, XRF

ARTICLE INFORMATION

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1. Introduction

Coal, one of the most important fossil energy resources is widely used for heat generation, cement industries, metal smelting, power production and various industrial applications (Yazdi, 1359). The importance of coal does not depend only on the amount of reserves or ease of extraction but also on its quality, which plays a fundamental role in determining its industrial applicability, fuel value and environmental impacts (Amriansyah & Sihombing, 2021). The quality of coal is related to a series of physical, chemical and thermal parameters, of which moisture content, ash yield, volatile matter, carbon content, Sulphur concentration, elemental composition and calorific value are considered the most important indicators (Zhu, 2014).

Proximate coal analysis determines the contents of moisture, ash and volatile matter. Fixed carbon is calculated from the measured parameters. This method is acknowledged as the foundation of the proximate coal analysis in the internationally accepted standards like ASTM D7582 and ISO 17246 (Coal and Coke, 2010).

Ash content is one of the main indicators of coal quality as high ash values are usually indicative of high concentrations of noncombustible mineral matter and possible contamination of coal with surrounding host rocks. The increase of ash content can significantly reduce the calorific value of coal and increase the amount of solid residue generated after burning (Majumder et al., 2008). Volatile matter is another important parameter for understanding the combustion behaviour of coal as its concentration affects the ignition characteristics, flame properties and degree of coalification (Khatami & Levendis, 2016). The composition of minerals and trace elements is also of vital importance in assessing the quality of the coal and its environmental implications (Finkelman et al., 2019).

According to the United States Geological Survey (USGS), coal rank is closely related to parameters including fixed carbon, moisture content, volatile matter, and calorific value. The main coal classes, from lignite to anthracite, are differentiated based on these characteristics (Pierce & Dennen, 2009). Proximate analysis of coal generally involves determination of moisture, ash, volatile matter and fixed carbon contents. These parameters are widely used for estimation of combustion behavior, comparison

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of coal quality and estimation of calorific value (Majumder et al., 2008; Gupta, 2007). Generally, with increasing coalification rank, moisture and volatile matter contents decrease and fixed carbon content and calorific value increase. Consequently, coal changes to higher-rank stages such as bituminous coal and anthracite and lower-rank stages such as lignite (Tan et al., 2015; Dai et al., 2012).

Volatile matter is the component of coal that is evolved as gases and volatile compounds when the sample is heated in the absence of oxygen. Its concentration is very important in determining coal rank and burning characteristics (Gupta, 2007). Moisture may be free water, adsorbed water in pores and fractures or water associated with certain minerals accompanying the coal. Moisture has generally negative effect on calorific value and fuel efficiency (Majumder et al., 2008; Tan et al., 2015). Also, of significant importance in industrial and environmental terms are undesirable elements and compounds such as sulfur, phosphorus, chlorine and nitrogen. Many of these components are retained in associated minerals such as pyrite, apatite, carbonates, sulfates and clay minerals which can cause technical and environmental problems during the utilization and combustion processes of coal (Finkelman et al., 2019; Mesroghli et al., 2009).

The main aim of this study is to perform the preliminary evaluation of coal quality indices and elemental composition of Gazestan coal mine in Takhar Province based on XRF analysis and thermal treatment testing. The present work aims to study the major differences in elemental composition, ash yield and volatile matter/moisture content between coal samples and to identify the limitations of the available data for future detailed investigations.

2. Literature survey

For the evaluation of coal quality, scientific research commonly uses proximate analysis, ultimate analysis, calorific value determination, and elemental composition analysis. Accordingly, the present study on the Gazestan coal deposit in Takhar Province was carried out using XRF analysis and preliminary thermal treatment tests. In global studies, comprehensive coal quality evaluation is generally performed through the integration of several laboratory techniques, including proximate analysis, ultimate analysis, XRD, SEM–EDS, ED-XRF, and ICP-OES, in order to determine both fuel characteristics and the composition of mineral and trace elements (Coal and Coke, 2010; Junussov et al., 2025). Recent studies have further confirmed that ash content together with calorific value are one of the most important indicators for establishing the commercial rank, classification and industrial applicability of coal (Mishra et al., 2025).

Afghanistan possesses moderate to potentially significant coal resources; however, a considerable proportion of these deposits are found in relatively deep or less accessible areas and this has limited their development. Historically, Afghanistan's domestic coal has been used for small-scale industries, such as cement production, textile manufacturing, and food processing, and for household fuel consumption (SanFilipo, 2005). The studies on Afghanistan's coal potential show that the previous work was mainly on the delineation of reserve limits without systematic evaluation of quality and detailed characterization studies of coal properties are still limited in many parts of the country (Wnuk, 2024). In recent years, several studies have attempted to investigate the characteristics of Afghan coal deposits by statistical approaches and modeling techniques (Chehreh Chelgani, 2023). Furthermore, recent reports show that traditional mining operations in coal-bearing strata have been significantly increased (Wnuk, 2016).

2.1 Research gap

Most previous studies on coal in Afghanistan have dealt with the identification of coal-bearing basins, estimation of reserves, general location of deposits and regional geological settings. The Nahrin, Chal – Namak Ab coalfield and coal occurrences in Takhar Province are also mentioned by domestic sources. However, laboratory information on coal quality parameters and elemental composition from the Gazestan mine is rare and scattered. Most of the available studies have concentrated on general resource description, spatial distribution, reserves or geological characteristics, but key quality-related parameters such as ash content, volatile matter/moisture, sulfur concentration, mineral constituents and trace elements have not yet been systematically studied in this mining area.

3. Problem definition

Coal-bearing areas like Gazestan coal mine in Takhar Province are found in northeastern Afghanistan. But there is lack of sufficient and systematically organized laboratory data on quality parameters and elemental composition of coal. The absence of key data sets such as ash content, volatile matter, moisture, fixed carbon, calorific value, sulfur content and mineral constituents limits the ability to properly assess the fuel quality, industrial applicability and environmental implications of Gazestan coal.

This study, the available data are XRF analysis and thermal treatment tests on three coal samples obtained from the second mining gallery of the Gazestan mine. This work is considered as preliminary evaluation since detailed proximate analysis, calorific value determination, total sulfur content measurement and separation of moisture from volatile matter were not carried out.

The main research question of this study is to determine what variations exist among the Gazestan coal samples in terms of elemental composition, ash content, and volatile matter/moisture, based on the available data, and what implications these variations may have for coal quality evaluation, industrial utilization, and future detailed investigations.

4. Study area

4.1 Geographical location

In Afghanistan, nine coal mines and more than 42 coal occurrences have been identified, most of which are located in the northern part of the country. The coal-bearing belt extends in a linear form for approximately 700 km from the east of the Farakh River to Sabzak, and includes five major coalfields: Sabzak, Dara-e-Suf, Sayghan–Ashpushta, Pul-e-Khumri, and Naharin–Chal–Namak Ab (Fakhruddin, 1390)

The study areas are located in Takhar Province in northeastern Afghanistan. The Gazestan coal mine is situated in the Kalafgan District. These areas lie within the northeastern extension of the Afghan coal belt, and this geological setting is of considerable significance for coal-related geological studies and quality assessment. The geographical location of the study area is shown in Figure 1.

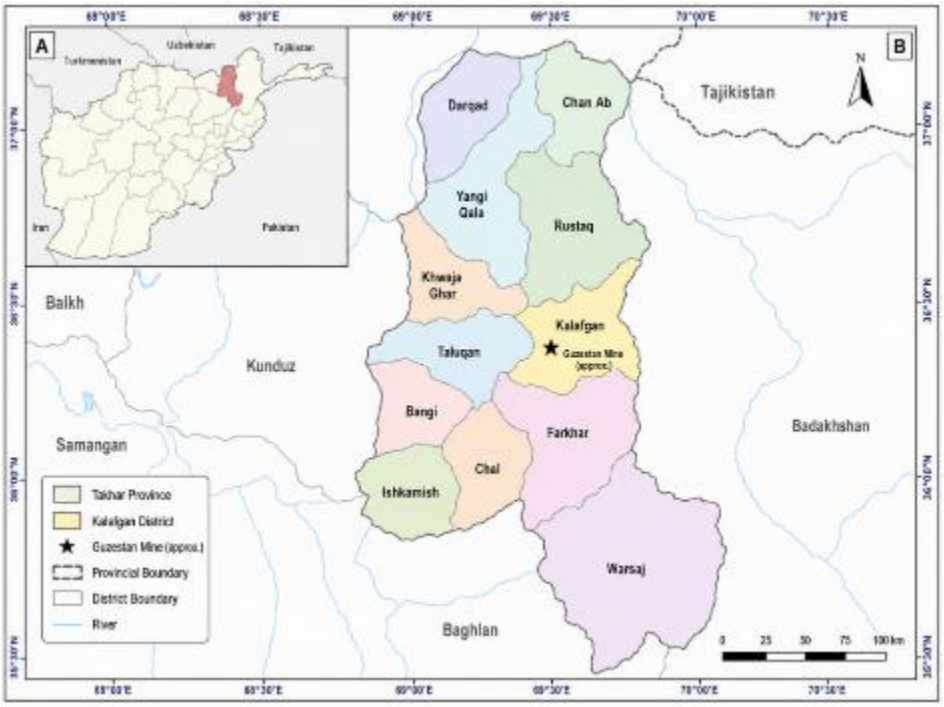


Figure 1. Geographic location of the Gazestan coal mine in Takhar Province

4.2 Geology of the area

The study area falls within the sedimentary-mineralogical units of the Afghan-Tajik Basin. According to the USGS, the outcrops in the Takhar Province are mainly Cretaceous to recent sediments. The units of the Mesozoic and early Cenozoic include marine, lagoonal and continental deposits, with evaporitic units consisting of gypsum and anhydrite (Orris, 2011).

In addition, USGS remote sensing data indicate spatial association of known coal occurrences in the Takhar region with kaolinite-bearing units, kaolinite mixed with muscovite–clay–calcite assemblages, and calcite associated with muscovite. These associations suggest that clay-rich, carbonate-bearing, and Jurassic sedimentary units play an important role in the occurrence and characteristics of coal in Takhar Province (Chornack, 2011). Geological mapping at the scale of 1:200,000 also indicates that several mineral occurrences in the Naharin–Chal–Namak Ab area, such as Chal, Zanburak and Bazarek, have been explored. This region exhibits distinctive geotectonic, facies, and coal accumulation characteristics (Hare et al., 2008).

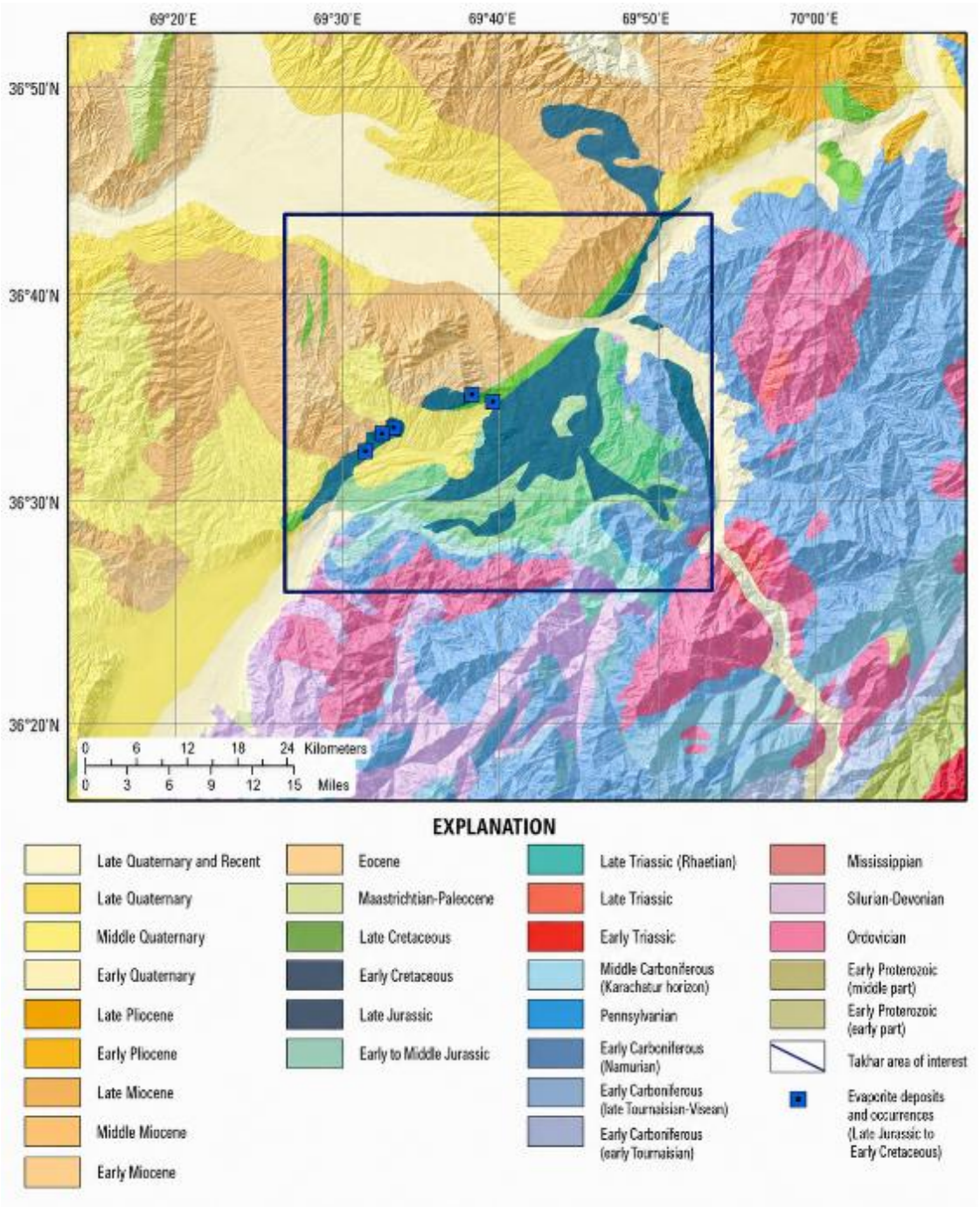


Figure 2. Takhar area of interest geology distribution of evaporite deposits and occurrences (Doebrich & Wahl, 2006).

For the Gazestan mine, field observations from the present study indicate that the coal seam occurs in a lenticular form within sandstone and conglomerate units. Therefore, the evaluation of coal quality in the Gazestan area must consider geological heterogeneity, sampling limitations, and variations in host rock lithology.

4.3 Sampling sites

Field observations reported that the Gazestan coal mine is accessed by two inclined shafts with an approximate dip of 35°. The inclined shafts are separated by approximately 30 m and are connected by an auxiliary crosscut. The coal seam locally reaches a thickness of about 1.60–2.0 m, in places the width varies between 1.20 and 1.80 m.



Figure 3. Second inclined shaft of the Gazestan coal mine.

5. Methodology

5.1 Field sampling

Coal samples studied in this paper were collected from different parts of the coal seam of the Gazestan mine along the mining gallery. Based on field observations, sampling was conducted at distances of approximately 120–200 m from the portal of the second inclined shaft and from three distinct positions within the coal-bearing strata. The sampling locations were chosen to best represent the observable spatial and lithological variations of the coal seam along the gallery.

Each sample collected during the sampling was placed in a separate container and labeled with a unique identification code to prevent cross-contamination or mixing of samples. Table 1 shows the general characteristics of the samples. The relative positions of the samples along the gallery and field observations were then used to support the interpretation of the analytical results in this study.

Table 1. Characteristics of coal samples collected from the Gazestan coal seam for XRF analysis

Sample Code	Sampling Location (m)	Remarks
GZ-1	120	Upper seam section
GZ-2	160	Middle seam section
GZ-3	200	Lower seam section

5.2 Sample preparation

The obtained samples were taken to the laboratory for their preparation for XRF analysis and thermal treatment experiments. Sample preparation included preliminary cleaning, removal of visible impurities, crushing, grinding and homogenization. Each sample was then split into two parts for XRF analysis and thermal testing, respectively.

Samples were crushed, ground and homogenized prior to analysis to minimize the effects of sample heterogeneity. This step is very important for coal-related studies, because heterogeneity, apparent moisture, and admixture with host or gangue materials can have a great influence on ash content, volatile matter and elemental composition.

5.3 XRF analysis

XRF analysis was used to determine the elemental composition of coal samples. This technique was used to detect the major and trace elements present in the samples. The results indicated the presence of elements including Al, Si, Ca, Ti, S, K, Fe, Th, and U. In the reported tables, the parameter labeled "Bal" (balance) represents the residual fraction or instrument-calculated remainder and, in this study, was not directly interpreted as fixed carbon, organic matter, or the calorific value of coal. The results of the XRF are reported in weight percent (%) and parts per million (ppm). These data were used to assess relative differences in elemental composition between the samples.

5.4 Thermal treatment test

In this study thermal treatment was used as a preliminary method to evaluate the thermal weight loss and the residual solid fraction of the samples. Calculations were based on the mass of the initial sample and the mass remaining after heating. The residual fraction (ash content) was calculated as the ratio of the residual mass after heating to the initial mass and the % weight loss was calculated from the difference between the initial and residual masses .

Since the moisture and volatile matter were not measured separately, the observed thermal weight loss was not related to the volatile matter. Instead, it is only shown as an indication of the thermal behavior of the samples in the beginning.

5.5 Data analysis methodology

Descriptive and comparative analysis of data obtained by XRF analysis and thermal treatment experiments was performed. First, the reported elemental concentrations were examined, with a particular focus on the variations between the Gazestan samples. The residual fraction (ash content) and thermally induced weight loss for the samples were then compared. Since moisture and volatile matter were not measured separately, the observed weight loss was interpreted only as a preliminary indicator of thermal behavior. The number of samples was small, so only descriptive statistics could be calculated and the results were interpreted in a preliminary way.

6. Results and discussion

6.1 Field investigation results

Field studies indicated that Gazestan coal mine is developed in two open inclined shafts. The inclined shafts are at an inclination of some 35°, and spaced about 30 m apart. They are connected by a crosscut, which in normal conditions serves as a ventilation route, and in emergency situations, can also serve as an auxiliary transport or escape passage.

The inclined shafts are supported by timber supports, which are props and sets (caps and legs). The observations in the field showed that this type of timber support is widely used in the Gazestan mine, but the support installation was not done in a fully standardized way in some parts of the gallery. These observations suggest that mining conditions should be more focused on safety and control of possible roof instability or fall of gangue material.

The coal seam of the Gazestan mine is in lenticular shape, hosted in sandstone and conglomerate formations. Field observations show that at some localities the seam thickness varies from about 1.60 to 2.00 m and the exposed width from 1.20 to 1.80 m. The three samples used in this study (GZ-1, GZ-2 and GZ-3) were taken from the second inclined shaft at approximate distances of 120, 160 and 200 m from the shaft entrance (portal). This sampling strategy enabled a preliminary assessment of coal quality variation along the shaft.

Field observations also indicate that coal in the Gazestan mine is extracted via an inclined shaft and the extracted material is transported by rails and mine wagons. A general view of the inclined shaft entrance and the wagon system used for coal transport is presented in Figure 4.



(a) (b)

Figure 4. Field conditions of the production inclined shaft in the Gazestan mine: (a) entrance of the inclined shaft and rail track; (b) internal view of the inclined shaft showing timber supports and the coal transportation system

As shown in Figure 4, coal extraction and transportation in the Gazestan coal mine are carried out in a semi-mechanized manner using rail tracks and mine wagons. This operational condition indicates that during extraction and haulage, there is a potential for mixing of coal with host rocks, roof fall materials, and surface particulates. Therefore, sampling from different parts of the coal seam is essential for identifying potential variations in coal quality.

After being transported from the underground workings, the extracted material is accumulated in the surface area of the mine and subsequently prepared for further transportation. Figure 5 illustrates that the mined coal is stored in irregular stockpiles in the mine's surface yard. Such storage conditions may lead to the mixing of coal with different quality grades.



Figure 5. Accumulation of extracted coal in the surface storage area of the Gazestan mine.

6.2 XRF analysis results

The results of XRF analysis of three coal samples of Gazestan mine are presented in Table 2. The findings indicate that the elemental composition of the samples is not uniform, and elements such as Al, Si, Ca, Ti, K, Fe, Sc, S, Th, and U are reported at varying concentrations across the different samples. The "Bal" value reported in the XRF table is the residual fraction. In this study, it was regarded as the unquantified part of the coal composition or as a complementary component of the total composition and was not directly interpreted as a volatile matter.

Table 2. XRF results of coal samples of Gazestan mine

Sample Code	Location	Al (%)	Si (%)	Ca (%)	Ti (%)	K (%)	Fe (%)	Sc (%)	S (ppm)	Th (ppm)	U (ppm)	Bal (%)
GZ-1	Gazestan	0.14	0.36	2.26	0.38	–	0.82	–	872	7	5	96.00
GZ-2	Gazestan	0.13	0.32	0.11	0.56	0.50	0.16	–	328	15	6	98.48
GZ-3	Gazestan	–	0.32	8.68	–	–	0.21	0.14	263	–	–	90.54

Note: The symbol "–" indicates that the element was not reported in the laboratory table. The "Bal" value represents the residual fraction of the coal composition.

Table 2 shows that the Gazestan samples have only a small range of Si contents (0.32–0.36%). Such limited variation indicates that Si is relatively homogeneous in the three samples investigated, compared to the other elements measured. However, Ca shows a marked variation (maximum 8.68% in GZ-3 against 0.11% and 2.26% in GZ-2 and GZ-1. The difference is so large that GZ-3 can be clearly separated from the other two samples in terms of calcium-bearing constituents.

The Fe content is also different in the three samples. The highest Fe content is observed in GZ-1 (0.82%) and decreases to 0.16 % in GZ-2 and 0.21 % in GZ-3. This tendency indicates that GZ-1 is relatively enriched in Fe-bearing components compared to the other samples. The sulfur content also follows a decreasing trend along the second inclined shaft, decreasing from 872 ppm in GZ-1 to 328 ppm in GZ-2 and 263 ppm in GZ-3. This variation indicates that the distribution of sulfur may be non-homogeneous along the studied segment of a seam.

Figure 6 shows that GZ-1 has the highest concentration of sulfur among the investigated samples, while GZ-2 and GZ-3 are different in sulfur content. A gradual decline of the sulfur concentration from GZ-1 to GZ-3 is noted along the investigated section of the second inclined shaft. The XRF analysis results also indicate that GZ-1, which was collected closer to the shaft

entrance, has relatively higher concentrations of sulfur and detectable radioactive trace elements (Th and U). These observations may represent relatively greater environmental relevance and warrant further investigation. In contrast, the GZ-3 sample, collected about 200 m away from the shaft entrance, has a low sulfur concentration and does not contain detectable amounts of radioactive trace elements, indicating a comparatively lower environmental concern.

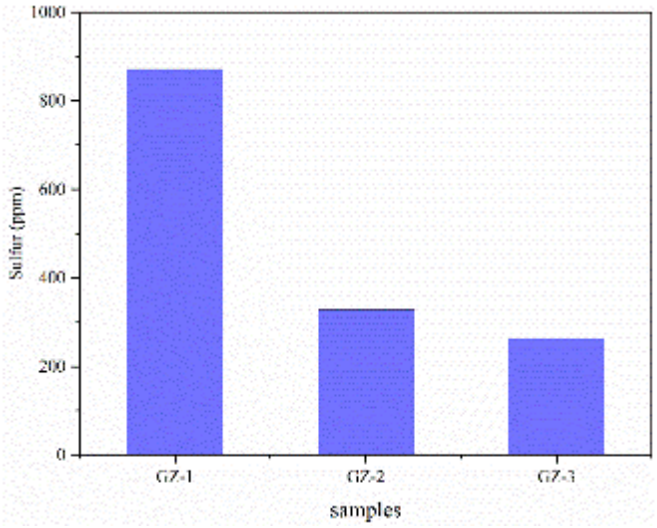


Figure 6. Sulfur analysis of coal samples from the Gazestan mine.

Figure 7 shows the variation of Ca and Fe in the three samples. Ca shows a significant increase in GZ-3 while the highest concentration of Fe is found in GZ-1. Such a pattern indicates the variability of the mineral related components and the non-uniform distribution of these components in the studied samples.

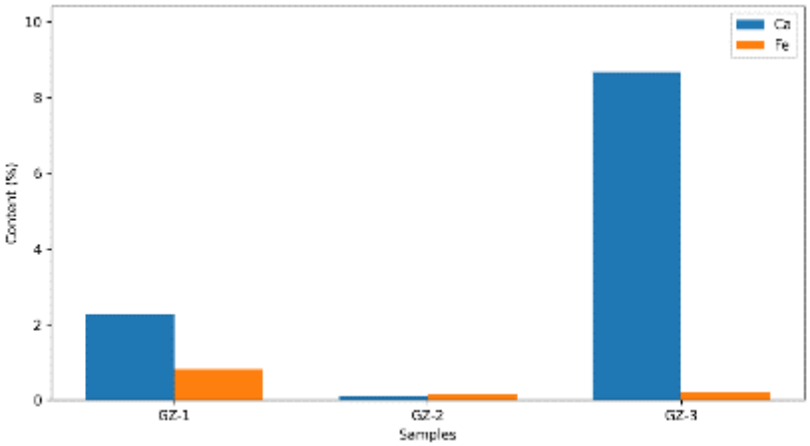


Figure 7. Comparison of Ca and Fe contents in coal samples from the Gazestan mine.

6.3 Thermal treatment test results

The results of the thermal treatment experiments on coal samples from the Gazestan mine are shown in Table 3. These results indicate notable differences in residual fraction (ash content) and thermally induced weight loss among the three samples. The ash content varies distinctly from 29.77% in GZ-3 to 69.90% in GZ-2. This difference of a factor 2 or more reflects a significant variation in the amount of non-combustible mineral matter in the samples. The results further indicate that samples taken nearer to the shaft entry tend to show higher ash yields, whereas GZ-3, which was collected at a further distance along the shaft, exhibits lower ash content and may therefore suggest comparatively lower mineral matter content and potentially more favourable coal characteristics.

Table 3. Results of thermal treatment tests for coal samples

Sample Code	Location	Ash Content (%)	Volatile Matter + Moisture (%)	Reported Coal Type (Laboratory)	Remarks
GZ-1	Gazestan	43.90	56.04	Lignite	Preliminary classification; requires reassessment
GZ-2	Gazestan	69.90	30.06	Lignite	Very high ash

Sample Code	Location	Ash Content (%)	Volatile Matter + Moisture (%)	Reported Coal Type (Laboratory)	Remarks
					content
GZ-3	Gazestan	29.77	70.22	Bituminous	Requires further detailed evaluation

The GZ-2 sample, which was sampled near the surface, has the highest ash content (69.90%) of all the samples studied, and is thus the most ash-rich sample. In this respect it is very different from GZ-3. GZ-3, obtained from a greater depth, has the lowest content of ash (29.77%). The coal from Gazestan deposit at around 200 m depth can be classified as bituminous coal according to international coal classification standards, which indicates relatively better quality. The ash content of the collected samples from the Gazestan mine is illustrated in Figure 8.

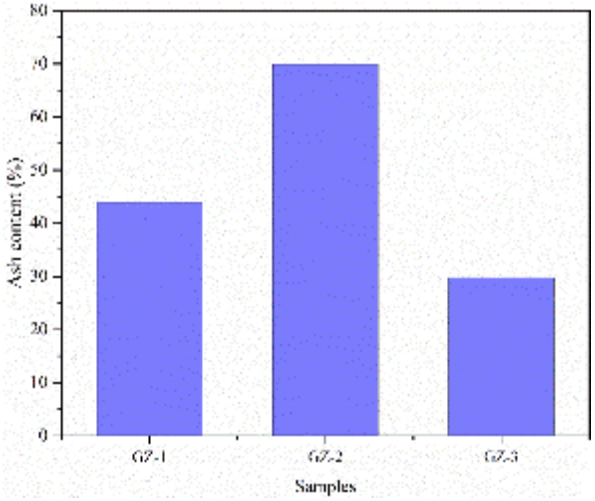


Figure 8. Comparison of ash content in coal samples from the Gazestan mine.

Figure. 9 shows the total thermally induced weight loss (volatile matter + moisture indicator) for the three samples. The lowest values are observed in GZ-1 and GZ-2, while the highest value (70.22%) is observed in GZ-3. This pattern could indicate, relatively, the differences in the thermal behavior and combustible fraction among the investigated samples. However, since moisture and volatile matter were not measured separately, this parameter is considered only a preliminary indicator and should not be interpreted as a direct measure of coal quality.

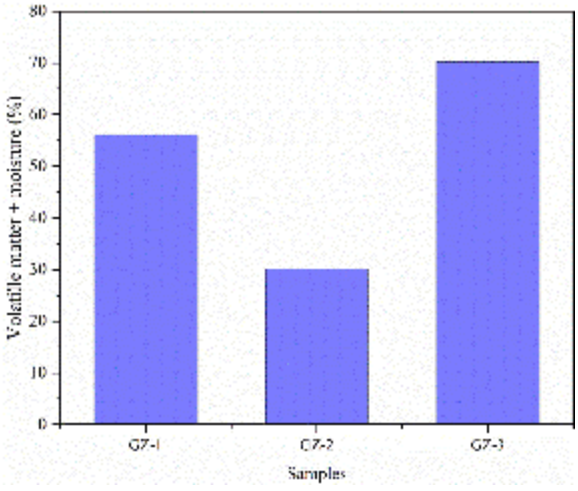


Figure 9. Comparison of volatile matter plus moisture in coal samples from the Gazestan mine.

The variation trend of ash content and volatile matter plus moisture along the inclined shaft indicates that changes in coal quality are not linear or simple. From GZ-1 to GZ-2, ash content increases while volatile matter and moisture decrease; however, from GZ-2 to GZ-3, ash content decreases and volatile matter plus moisture increases. Figure 10 illustrates that GZ-3 shows an increase in volatile matter plus moisture and therefore exhibits comparatively better coal quality.

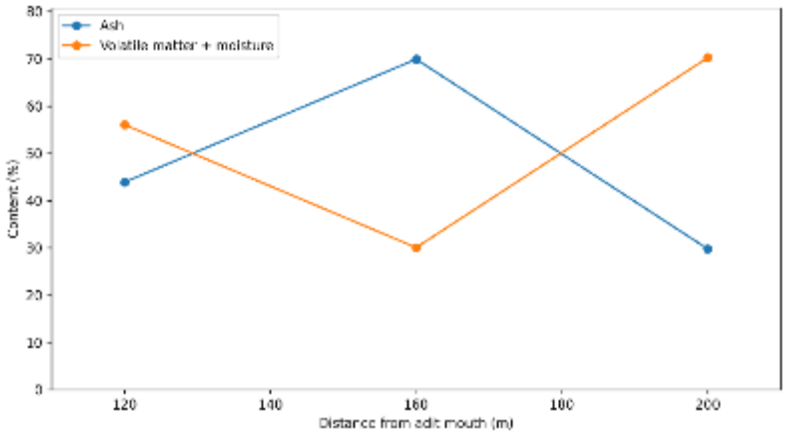


Figure 10. Trend of variation in ash content and volatile matter along the second inclined shaft

The trend of sulfur variation also shows that its concentration decreases from 872 ppm in GZ-1 to 328 ppm in GZ-2, and further to 263 ppm in GZ-3. This continuous decrease indicates that sulfur exhibits a different spatial behavior along the sampling profile compared to ash content and volatile matter. This trend is illustrated in Figure 11.

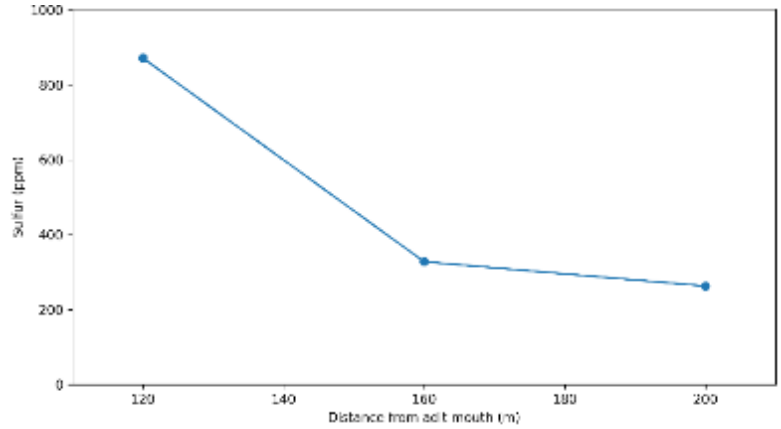


Figure 11. Trend of variation in sulfur content along the second inclined shaft of the Gazestan mine.

The variation trends of Ca and Fe show distinct differences among the investigated samples. Fe concentration decreases from 0.82% in GZ-1 to 0.16 % in GZ-2 and then slightly increases to 0.21 % in GZ-3. In contrast, Ca decreases from 2.26 % in GZ-1 to 0.11 % in GZ-2 before increasing to 8.68 % in GZ-3. Figure 12 illustrates the contrasting variation patterns of Ca and Fe among the samples.

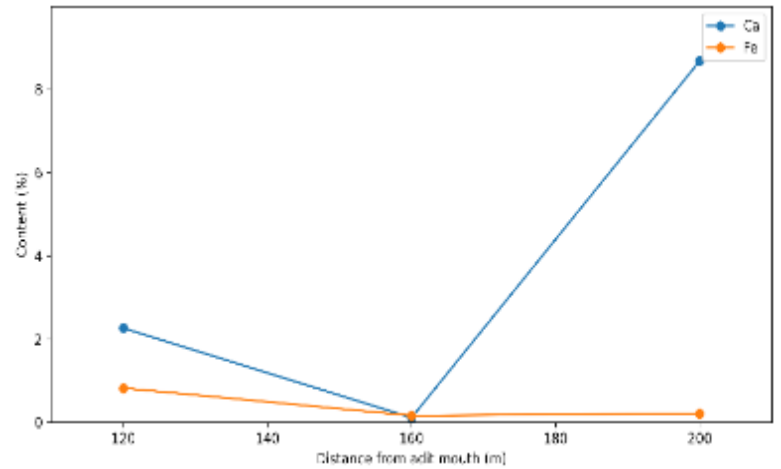


Figure 12. Variation trend of Ca and Fe contents in the inclined shaft

6.4 Discussion

The results of this study indicate that the coal of the Gazestan mine has significant heterogeneity in composition of elements, ash and thermal characteristics. It indicates non-uniformity of coal properties along the second inclined shaft. The pronounced differences between samples GZ-1, GZ-2 and GZ-3 can be explained by variation of depositional conditions, admixture with host rocks, the presence of associated mineral matter and local geological settings. Similar observations have also been reported in

international studies, with heterogeneity being a common feature of coal seams that can lead to large variations in ash yield, elemental composition, calorific value and combustion behavior (Finkelman et al., 2019; Gupta, 2007).

XRF results showed that the distribution patterns of Ca, Fe and S were different in studied samples. The highest Fe and S contents were found in GZ-1, while the highest Ca content and the lowest S content were found in GZ-3. Previous studies have indicated that Fe and S in coal are generally associated with sulfide minerals especially pyrite and may influence the combustion behavior, equipment corrosion and sulfur related emissions (Mesroghli et al., 2009). The high concentrations of Fe and S in GZ-1 may suggest the presence of sulfide-bearing phases. In contrast, the high Ca content in GZ-3 may be due to a higher abundance of carbonate minerals (e.g., calcite), or the influence of carbonate-bearing lithologies in the deeper section of the seam. Additional geochemical studies suggest that carbonate minerals may influence the behavior of ash and contribute to the relative reduction of Sulphur-related emissions during combustion (Finkelman et al., 2019).

One of the important observations of this study is the significant difference of ash content in the studied samples. The ash content varies from 29.77% in GZ-3 to 69.90% in GZ-2, indicating significant differences in the amount of non-combustible mineral matter. These ash contents are relatively high when compared with values reported in international studies, especially in GZ-2,. High ash content is generally associated with lower calorific value, higher fuel consumption and higher volumes of solid waste during industrial utilization (Majumder et al., 2008). Previous studies have pointed out that ash content is also a significant parameter in coal evaluation and in the assessment of industrial usability (Mishra et al., 2025). The very high ash content noted for GZ-2 could thus be due to increased admixture with host rocks or the presence of fine-grained mineral matter in the coal matrix. In contrast, GZ-3, which shows the least ash and sulfur contents in the studied samples, might indicate relatively more favorable fuel-related characteristics. The calorific value and fixed carbon were not measured in this study, but the lower ash and sulfur contents and the differences in thermally induced weight loss (volatile matter + moisture indicator) may reflect differences in coal composition, mineral matter content, or possibly coalification-related features in deeper parts of the seam. Earlier studies on coal quality have shown that lower mineral matter and ash contents are generally correlated with better fuel performance and higher industrial utilization (Tan et al., 2015).

The results also show that changes in coal characteristics can be affected by sampling position along the inclined shaft. Samples obtained near the shaft entrance, especially GZ-1 and GZ-2, show relatively higher ash and sulfur contents, and GZ-3, obtained farther down the inclined shaft, shows lower ash and sulfur contents and relatively better fuel-related characteristics. This pattern is generally consistent with international studies that indicate that near-surface coal seams are more susceptible to weathering, oxidation and admixture with surrounding sediments (Zhu, 2014). Therefore, the shallow parts of the Gazestan deposit are probably more affected by weathering and lithological mixing.

From an industrial point of view, the results emphasize the importance of selective mining and quality-based separation for improving the final coal product. The extraction and mixing of high-ash and low-ash coal without segregation may lead to a decline in fuel quality and an increase in the generation of solid waste. Studies on coal beneficiation have demonstrated that coal washing, gravity separation and controlled sizing are effective in reducing ash content and improving the fuel quality especially in the presence of mineral matter in liberated or semi-liberated forms (Majumder et al., 2008). Therefore, the washability and beneficiation potential of the Gazestan coal in the future studies is very important.

These results are also relevant from the point of view of the environment. The relatively high ash content of some samples may result in higher generation of solid waste and higher particulate emissions during or after combustion. Furthermore, the occurrence of trace elements such as U and Th even at low concentrations indicates the need for further assessment of their behaviour in coal ash and combustion residues. Previous studies have shown that trace elements in coal ash can be enriched or concentrated, which may present environmental risks if combustion by-products are not managed properly (Lu et al., 2025; Wang et al., 2025).

Comparison of the measured elemental concentrations with the international guideline values presented in Table 4 provides further insight into the environmental and industrial implications of Gazestan coal. The Fe and S contents of the studied samples are in the low-range of risk, which reduces the concern for S-related emissions and effects of pyrite during combustion. Similarly, the detected U and Th concentrations seem to be relatively low but their presence deserves further attention, as trace radioactive elements may be concentrated in combustion residues. On the other hand, GZ-3 Ca content is classified in the middle range by the guideline, which could be attributed to the existence of carbonate-bearing mineral matter and could influence the ash behavior during combustion. Generally, these observations lead to the conclusion that there is a certain geochemical variability of the samples, but the investigated coal does not demonstrate increased concentrations of potentially harmful elements according to the preliminarily available data.

Table 4. Literature-based comparative ranges for selected elements in coal adapted from (Swaine & Goodarzi, 1995)

Element	Low Risk	Moderate Level	High Risk	Geochemical and Environmental Significance
Fe (%)	< 1%	1–3%	> 3%	Pyrite association, combustion behavior

Element	Low Risk	Moderate Level	High Risk	Geochemical and Environmental Significance
S (%)	< 1%	1–3%	> 3%	SO_2 emissions, acid rain
Ca (%)	< 5%	5–10%	> 10%	Ash behavior (slagging/fouling)
U (ppm)	< 3 ppm	3–10 ppm	> 10 ppm	Radiological risk in ash
Th (ppm)	< 5 ppm	5–15 ppm	> 15 ppm	Radiological risk in ash
Cs (ppm)	< 1–2 ppm	2–5 ppm	> 5 ppm	Rare; geochemical anomaly indicator

Overall, the results demonstrate that the Gazestan coal deposit is highly heterogeneous, and coal quality varies along the inclined shaft. This heterogeneity is likely controlled by depositional conditions, associated mineral matter, mixing with host rocks, and local geological factors. Despite the variability, the results show that the deeper parts of the deposit are relatively better in coal quality and contain lower levels of harmful elements on an international standard which means that the environmental impact will be limited in these parts. However, the findings should be considered in light of the study limitations. The number of samples is limited to three points along a single inclined shaft. Moisture and volatile matter were not measured separately, fixed carbon and calorific value were not determined, total sulfur was not quantified directly and XRF does not identify the mineralogical form of elements, so the findings should be considered as a preliminary assessment.

7. Conclusion

The aim of this study was to make a preliminary evaluation of the quality indices and elemental composition of coal of Gazestan mine in Takhar Province based on field observations, XRF analysis and thermal treatment tests. The results showed that the Gazestan coal seam is heterogeneous in the elemental composition, ash content and volatile matter + moisture, and the samples collected at different depths show significant differences.

XRF results indicate that elements associated with mineral matter, particularly Ca, Fe, S and trace radioactive elements, are more abundant in sample GZ-1, which may have potential environmental implications. This sample was taken near the surface and is found in relatively younger sedimentary formations. The thermal treatment results showed that the ash content of this sample was about 43%, indicating that it is not suitable for industrial or domestic applications in its current form.

XRF results showed that Ca is up to 8.68% in GZ-3, sulfur content is 263 ppm and no trace radioactive elements like uranium and thorium were detected. Therefore, this sample was not related to considerable environmental concerns. Thermal analysis revealed an ash content of about 29% which corresponds to bituminous coal under international standards, and is suitable for cement production and other industrial uses.

The results of the thermal treatment showed that the ash content in the samples varied from 29.77% to 69.90%. GZ-2 has the highest ash-bearing sample with an ash content of 69.90% while GZ-3 has the lowest ash content of 29.77%. Volatile matter plus moisture also varied between 30.06% and 70.22%. The results show that the sample GZ-3 is bituminous coal, which indicates an increase in the coal quality with depth in the Gazestan deposit.

8. Future scope

Considering the limitations of the present study, future work should focus on a more comprehensive evaluation of the Gazestan coal deposit. The detailed characterization of coal including calorific value, fixed carbon, moisture and volatile matter measured separately is essential in order to assess the coal quality and utilization potential in a more reliable way. In addition, mineralogical studies by XRD and SEM–EDS are suggested to better characterize associated mineral phases and enhance the understanding of the geochemical behavior of the coal.

It would also be useful to increase the number of samples along the seam length and depth for more robust statistical analysis and better spatial assessment of quality variations. Furthermore, studies on coal beneficiation potential to reduce ash and sulfur contents and environmental assessment of trace and naturally occurring radioactive elements in coal ash especially U and Th are recommended. Such investigations could contribute to improved mining management, environmental protection, and more efficient industrial utilization of the Gazestan coal deposit.

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10. Abbreviations

XRF: X-ray Fluorescence
XRD: X-ray Diffraction
SEM–EDS: Scanning Electron Microscopy–Energy Dispersive Spectroscopy
ASTM: ASTM International (formerly American Society for Testing and Materials)
ISO: International Organization for Standardisation

ppm: parts per million
GZ: Gazestan
U: Uranium
Th: Thorium
Ca: Calcium
Fe: Iron
S: Sulfur

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