

Sampling Source and Coal Grade: Assessing Variability in Proximate Properties and Gross Calorific Value

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Abstract— Coal quality is heterogeneous at scales relevant to mining, sampling and utilization, and the point at which a sample is collected may influence the quality that is reported for a mining operation. This study evaluates sampling-source-dependent variability in coal from Sharda Underground Mine, Kanhan Area, Western Coalfields Limited, Madhya Pradesh, India. Coal samples collected as drill, seam and belt samples were examined for moisture, ash, dry-basis volatile matter, fixed carbon and gross calorific value (GCV). Three observations were available for each sampling source. Drill and seam samples showed closely comparable GCVs of 4651.18 and 4623.04 kcal/kg, respectively, whereas belt samples averaged 4116.68 kcal/kg. The corresponding mean ash contents were 34.12%, 35.90% and 43.14%, while mean fixed-carbon contents were 35.33%, 35.21% and 30.20%, respectively. Under the Indian non-coking coal GCV classification, the drill and seam samples fall within G9, whereas the belt samples fall within G11. Thus, the observed sampling-source difference was sufficiently large to change the apparent GCV-based grade of the sampled material. The results demonstrate that representative sampling is important when coal quality is assessed for grading or utilization and that a single sampling point may not adequately represent the quality of the material moving through an underground mining operation. The study is presented as a mine-level case study and provides a basis for larger, time-resolved sampling programs in Central Indian coal mines.

Keywords— Coal Heterogeneity, Representative Sampling, Coal Sampling, Proximate Analysis, Gross Calorific Value, Indian Coal, Western Coalfields, GCV-based Grading.

I. INTRODUCTION

Coal is a heterogeneous sedimentary fuel composed of organic matter together with variable proportions of mineral matter. Consequently, its chemical and energy-related properties can change over relatively short spatial scales and according to the material selected for sampling. This heterogeneity is particularly important for coal-quality measurement because sampling, sample preparation and analysis represent successive sources of variability. Sampling theory and coal-quality practice therefore emphasize that the collected sample should represent the population of coal for which the analytical result will be used (Moodley and Minnitt, 2009; Hand, 2014; Thomas, 2020).

The representativeness problem becomes more relevant when samples are collected at different stages of the mining system. Drill cores and seam or face samples are intended primarily to characterize coal in its geological occurrence, whereas samples taken from conveyors or other moving coal streams characterize material after extraction and handling. The two categories need not represent exactly the same material population. Differences may arise from inherent seam heterogeneity, out-of-seam dilution, mineral-matter distribution, particle segregation, selective extraction, handling and environmental exposure. Sampling standards therefore prescribe systematic procedures designed to reduce bias and obtain representative increments from heterogeneous coal streams (ASTM D2234/D2234M-20; ISO 18283:2022; BIS IS 436).

Proximate analysis remains one of the most widely used routine approaches for characterizing coal. Moisture, ash, volatile matter and fixed carbon provide complementary information on fuel composition and are closely associated with combustion and utilization behaviour (Lotfi and Jafari, 2018). Gross calorific value (GCV) provides the energy content of the fuel and is especially important in India because non-coking coal is classified commercially according to GCV. Empirical and experimental studies have repeatedly demonstrated relationships between proximate constituents and heating value,

particularly the negative influence of ash and moisture and the contribution of the combustible organic fraction represented by volatile matter and fixed carbon (Channiwala and Parikh, 2002; Parikh et al., 2005; Majumder et al., 2008; Aich et al., 2020; Kumari et al., 2019).

Indian Gondwana coals are commonly characterized by relatively high mineral-matter and ash contents, although substantial variation exists among coalfields, seams and individual samples. Studies from Singrauli and other Indian coalfields have documented variation in moisture, ash, volatile matter, fixed carbon and GCV and have linked compositional differences to coal quality and utilization (Dwivedi and Kumar, 2022; Sajid et al., 2022). Work on Indian coal has also shown that ash and moisture can exert strong effects on calorific value, making their measurement important for quality assessment (Saravanan et al., 2023; Kumari et al., 2019). Such evidence establishes the importance of heterogeneity, but most studies have focused on geological/seam variability, inter-mine comparisons, or prediction of coal properties rather than direct comparison of multiple sampling points within the same underground mine.

This distinction provides the motivation for the present study. A sampling-source comparison can address a practical question relevant to mine-level quality control: does the measured quality of coal remain sufficiently similar when samples are collected from different points in the mining and handling system? If not, the choice of sampling point may influence not only individual proximate parameters but also the GCV-based grade assigned to the material. Although representative sampling has been extensively addressed in standards and sampling literature, comparatively limited published work directly compares drill, seam and conveyor-belt samples from the same underground Indian mining operation.

The present study therefore examines coal from Sharda Underground Mine in the Kanhan Area of Western Coalfields Limited, Madhya Pradesh. Moisture, ash, dry-basis volatile matter, fixed carbon and GCV are compared for drill, seam and belt samples. The objectives are to (i) quantify differences among the three sampling sources, (ii) examine how these differences are reflected in GCV and Indian coal-grade classification, and (iii) interpret the findings in relation to representative sampling and coal heterogeneity. The study is intentionally framed as a mine-level case study; the dataset is not intended to provide a mine-wide statistical estimate of coal quality.

II. MATERIALS AND METHODS

2.1 Study Area and Sampling Framework

The study was conducted at Sharda Underground Mine, Kanhan Area, Western Coalfields Limited, Madhya Pradesh, India. The sampling framework comprised three sources representing different stages or contexts of the coal system: drill samples, seam samples and belt-conveyor samples. The underlying dissertation describes representative sampling, sample mixing, crushing, division and pulverization as important steps in obtaining analytical samples from heterogeneous coal. The present paper retains the original source categories so that differences among the sampled populations can be examined directly (Sharma, 2023).

2.2 Sample Preparation and Laboratory Analysis

The collected coal material was prepared using the procedures documented in the underlying dissertation, including reduction and division of the gross sample before laboratory analysis (Sharma, 2023). Proximate parameters were determined using established coal-testing procedures. Moisture, ash, volatile matter and fixed carbon were reported as proximate quality parameters. GCV was determined by bomb calorimetry. The analytical framework followed Indian and international coal-testing practices, including BIS IS 1350 and ASTM procedures (BIS IS 1350; ASTM D3172; ASTM D5865; ISO 17246; Sharma, 2023).

2.3 Dataset and Statistical Treatment

The numerical dataset consisted of nine observations: three drill, three seam and three belt observations. Descriptive statistics were calculated separately for each sampling source using the arithmetic mean and standard deviation. Exploratory Pearson correlations were calculated for the pooled nine observations. Because the observations were collected in three distinct source groups and the number of observations per group was only three, these correlations are interpreted as descriptive associations rather than causal relationships.

Differences among the three sampling sources were additionally examined using the Kruskal–Wallis test. With $n = 3$ per group, the resulting p-values are treated as exploratory evidence rather than definitive population-level inference. No predictive models were fitted because the sample size is insufficient for reliable model development.

2.4 Coal-Grade Classification

The GCV results were interpreted using the Indian non-coking coal grade classification. Under the Ministry of Coal classification, G9 corresponds to GCV greater than 4600 and up to 4900 kcal/kg, G10 to greater than 4300 and up to 4600 kcal/kg, and G11 to greater than 4000 and up to 4300 kcal/kg. These thresholds were used to determine whether differences among sampling sources changed the apparent coal grade.

III. RESULTS

3.1 Individual Observations and Descriptive Statistics

The nine observations showed clear differences among sampling sources. Figure 1 summarizes the source-wise ash means, while Table 1 gives the individual observations and Table 2 gives the corresponding mean $\pm$ standard deviation values. Drill and seam samples were relatively similar, whereas belt samples consistently showed higher ash and lower fixed carbon and GCV. The individual observations and descriptive statistics are presented in Tables 1 and 2.

TABLE 1
INDIVIDUAL PROXIMATE-ANALYSIS AND GCV OBSERVATIONS FOR DRILL, SEAM AND BELT SAMPLES

Source	Ash (%)	Moisture (%)	Dry VM (%)	Fixed Carbon (%)	GCV (kcal/kg)	Grade
Drill	32.29	4.92	24.89	34.78	4651.29	G9
Seam	34.79	3.65	25.29	34.29	4623.22	G9
Belt	44.69	1.84	24.76	30.11	4117.65	G11
Drill	33.15	4.99	25.96	35.95	4651.49	G9
Seam	37.71	3.39	25.64	35.59	4622.23	G9
Belt	41.56	1.99	24.62	30.77	4115.98	G11
Drill	36.92	4.99	25.86	35.25	4650.76	G9
Seam	35.2	3.36	25.36	35.76	4623.66	G9
Belt	43.18	1.89	24.76	29.72	4116.42	G11

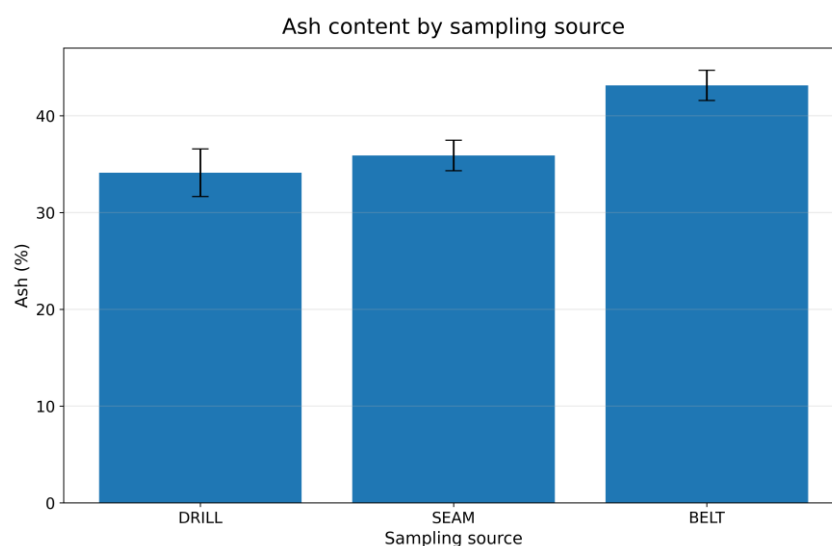


FIGURE 1: Mean ash content of drill, seam and belt samples; error bars represent ± 1 standard deviation (n = 3)

3.2 Sampling-Source Differences

The mean ash content increased from 34.12% in drill samples to 35.90% in seam samples and 43.14% in belt samples. Figure 2 shows the corresponding moisture and dry-basis volatile-matter patterns across the three sampling sources. The belt mean

was approximately 9.02 percentage points higher than the drill mean, corresponding to an increase of about 26.5% relative to the drill value. Moisture showed the opposite pattern, declining from 4.97% in drill samples to 3.47% in seam samples and 1.91% in belt samples. Dry-basis volatile matter was comparatively stable, with means of 25.57%, 25.43% and 24.71% for drill, seam and belt samples, respectively.

Fixed carbon was similar in drill and seam samples (35.33% and 35.21%) but substantially lower in the belt samples (30.20%). The mean GCV followed the fixed-carbon/ash pattern: 4651.18 kcal/kg for drill, 4623.04 kcal/kg for seam and 4116.68 kcal/kg for belt samples. Thus, the belt mean was approximately 534.50 kcal/kg lower than the drill mean, or 11.5% lower.

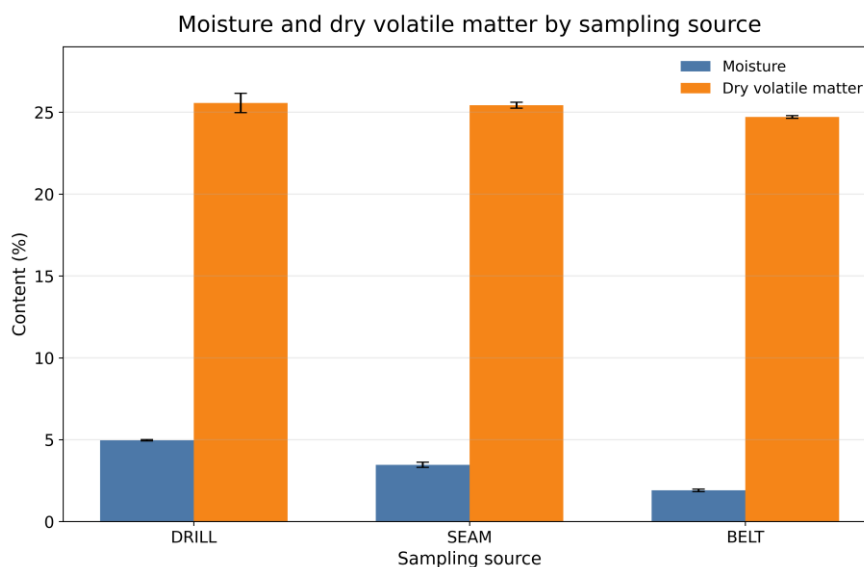


FIGURE 2: Mean moisture and dry-basis volatile matter by sampling source; error bars represent ± 1 standard deviation ($n = 3$)

3.3 GCV-Based Grade Classification

The difference in GCV has direct significance for Indian coal grading. Figure 3 shows the mean GCV values against the grade boundaries. The drill mean of 4651.18 kcal/kg and seam mean of 4623.04 kcal/kg both fall within G9 (>4600–4900 kcal/kg). In contrast, the belt mean of 4116.68 kcal/kg falls within G11 (>4000–4300 kcal/kg). All three individual drill observations and all three individual seam observations were classified as G9, while all three belt observations were classified as G11. The observed sampling-source difference therefore crossed two grade categories and was not attributable to a single anomalous observation.

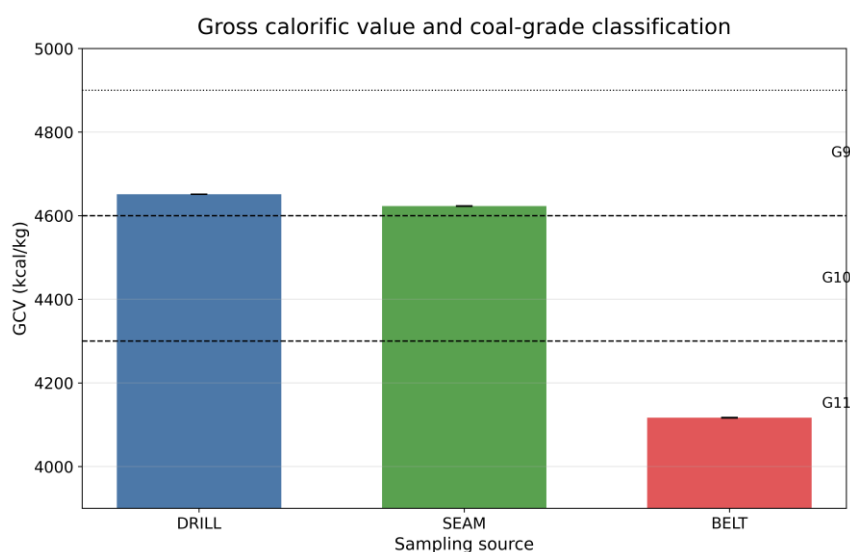


FIGURE 3: Mean GCV by sampling source with Indian non-coking coal grade boundaries; error bars represent ± 1 standard deviation ($n = 3$)

3.4 Exploratory Statistical Relationships

Across the nine pooled observations, Pearson correlation coefficients were strongly negative between ash and GCV ($r = -0.919$) and strongly positive between fixed carbon and GCV ($r = 0.976$). Moisture and dry volatile matter showed correlations with GCV of $r = 0.891$ and $r = 0.782$, respectively. The positive moisture–GCV association in the pooled dataset should not be interpreted as a causal fuel-quality relationship because the observations are clustered by sampling source and the belt group simultaneously has lower moisture and lower GCV. The correlations therefore primarily describe the structure of this small dataset.

Kruskal–Wallis testing provided exploratory evidence of differences among sources for moisture ($p = 0.0265$) and GCV ($p = 0.0273$), with ash close to the conventional 0.05 threshold ($p = 0.0509$). Differences for dry volatile matter ($p = 0.0594$) and fixed carbon ($p = 0.0665$) were not statistically significant at the 5% level. Given the very small group sizes, these results are used only as supporting evidence; the magnitude and consistency of the observed source differences are more important to the interpretation.

IV. DISCUSSION

4.1 Sampling Source and Apparent Coal Quality

The principal finding is that coal collected from three locations within the same mining operation did not produce equivalent quality profiles. The contrasting ash and GCV patterns are summarized in Figure 4. Drill and seam samples were closely comparable in both GCV and fixed carbon, whereas belt samples contained substantially more ash and correspondingly lower fixed carbon and GCV. The consistency of the belt result across all three observations indicates that the difference is not simply the result of one extreme measurement.

TABLE 2
MEAN $\pm$ STANDARD DEVIATION OF PROXIMATE PARAMETERS AND GCV BY SAMPLING SOURCE

Source	Ash (%)	Moisture (%)	Dry VM (%)	Fixed Carbon (%)	GCV (kcal/kg)
Drill	34.12 $\pm$ 2.46	4.97 $\pm$ 0.04	25.57 $\pm$ 0.59	35.33 $\pm$ 0.59	4651.18 $\pm$ 0.38
Seam	35.90 $\pm$ 1.58	3.47 $\pm$ 0.16	25.43 $\pm$ 0.19	35.21 $\pm$ 0.80	4623.04 $\pm$ 0.73
Belt	43.14 $\pm$ 1.57	1.91 $\pm$ 0.08	24.71 $\pm$ 0.08	30.20 $\pm$ 0.53	4116.68 $\pm$ 0.87

This observation is consistent with the broader sampling literature, which emphasizes that coal is a heterogeneous bulk material and that the sampling location and method influence which part of that heterogeneous population is represented. Moodley and Minnitt (2009) demonstrated that sampling can constitute a major component of total measurement variability, while Hand (2014) described sampling requirements across the coal chain. Thomas (2020) similarly distinguishes between in-situ samples such as drill cores and seam samples and ex-situ samples collected from coal streams and stockpiles. The present results provide a mine-level example of why this distinction matters analytically.

4.2 Ash Enrichment and Reduction in Energy Value

Ash was the parameter showing the clearest difference among the three sources. The belt samples averaged 43.14% ash compared with 34.12% in drill samples and 35.90% in seam samples. The associated decline in GCV is consistent with the established dilution effect of mineral matter: increasing non-combustible ash reduces the fraction of the sample contributing to combustion heat. Indian coal studies have repeatedly reported inverse relationships between ash and calorific value (Dwivedi and Kumar, 2022; Saravanan et al., 2023; Kumari et al., 2019).

Several mechanisms could plausibly contribute to the higher belt ash, including the distribution of mineral matter within the mined material, out-of-seam dilution, selective extraction, particle segregation during transport, or differences in the material represented by the sampling points. The present dataset does not distinguish among these mechanisms. Accordingly, the result should be interpreted as an observed sampling-source difference rather than evidence that conveyor handling itself caused ash enrichment.

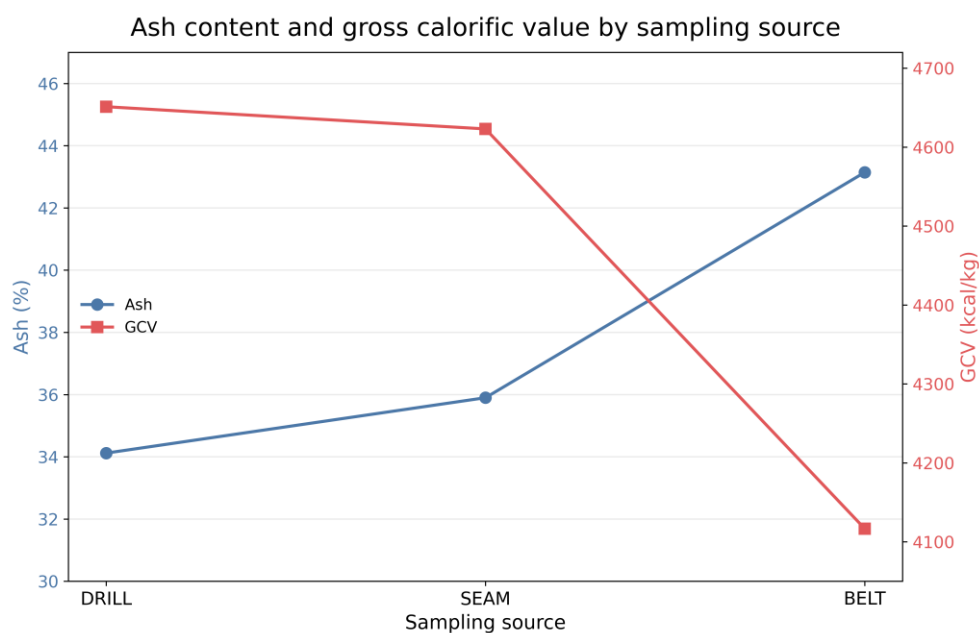


FIGURE 4: Sampling-source variation in mean ash content and GCV. The two y-axes are shown separately because the parameters have different units and numerical scales.

4.3 Fixed Carbon, Volatile Matter and GCV

Fixed carbon showed a pattern complementary to ash. The joint decline in fixed carbon and GCV at the belt source is illustrated in Figure 5. Drill and seam samples had means of approximately 35%, whereas belt samples averaged only 30.20%. Because fixed carbon is a major combustible fraction, its reduction occurred alongside the reduction in GCV. The strong positive pooled association between fixed carbon and GCV is directionally consistent with established fuel-composition relationships (Channiwalla and Parikh, 2002; Parikh et al., 2005; Majumder et al., 2008).

In contrast, dry-basis volatile matter changed little among sampling sources. The difference between drill and belt means was less than one percentage point. This suggests that the principal distinction among the present sample populations was not a broad change in volatile-matter characteristics but rather the balance between mineral matter and combustible carbonaceous material.

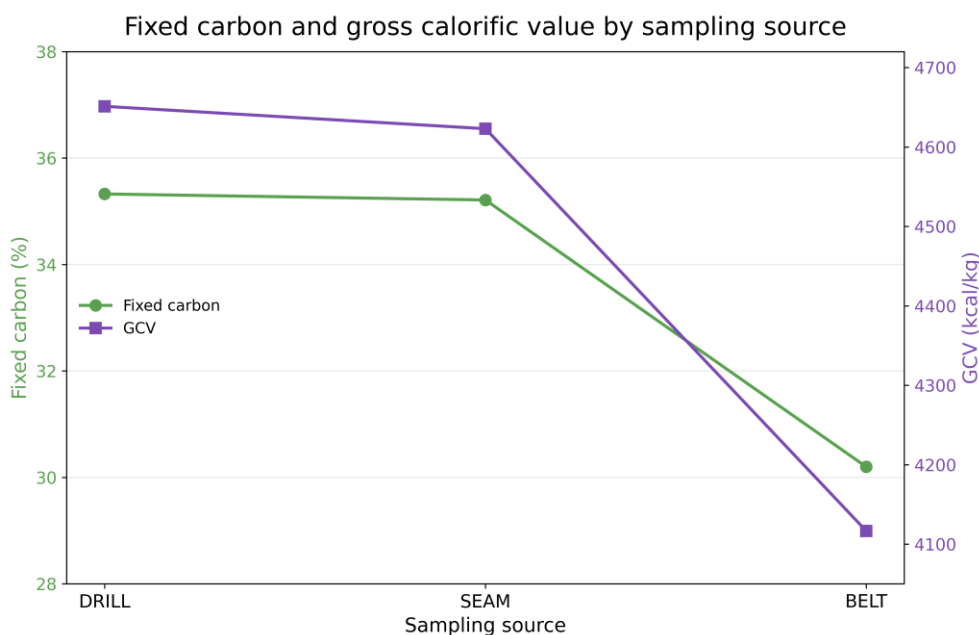


FIGURE 5: Sampling-source variation in mean fixed carbon and GCV. The two y-axes are shown separately because the parameters have different units and numerical scales.

4.4 Implications for Coal Grading and Quality Control

The most practically important result is the change in apparent grade from G9 for drill and seam samples to G11 for belt samples. Indian non-coking coal grades are defined by GCV, so a sampling-source difference of approximately 534 kcal/kg is sufficiently large to affect the reported grade. This has implications for quality control because a result obtained from an in-situ or geological sample should not automatically be assumed to represent the quality of the produced coal stream.

The result does not imply that one sampling source is universally superior. Rather, the appropriate sampling location depends on the question being asked. Drill and seam samples are valuable for characterizing geological coal quality, while conveyor-stream sampling is more directly relevant to the quality of the material actually being transported or delivered. For mine-level production and commercial quality assessment, representative sampling of the relevant moving coal population is therefore essential.

4.5 Comparison with Previous Studies

The magnitude and direction of the observed differences are broadly consistent with previous studies of Indian coal. Dwivedi and Kumar (2022) reported substantial variation in proximate properties and GCV among Singrauli coal samples, while Aich et al. (2020) demonstrated relationships between ash, fixed carbon, volatile matter and combustion behaviour in high-ash Indian coal. Saravanan et al. (2023) specifically examined the relationship between ash content and GCV in Indian coals. Studies from other Gondwana and Indian coal settings likewise demonstrate that seam position, lithological setting and coal composition can generate substantial quality variability (Banerjee and Chatterjee, 2021; Sajid et al., 2022).

The present study differs from these investigations primarily in its sampling-source perspective. Rather than comparing different mines or only different geological seams, it compares three sampling contexts within one underground mining operation. The study therefore complements geological variability studies by demonstrating that the definition of the sampled population itself can influence the measured quality profile.

4.6 Limitations and Implications for Further Work

The study has a deliberately limited dataset of three observations per sampling source. The results therefore should not be generalized as a mine-wide estimate of mean coal quality or as a definitive estimate of the magnitude of sampling bias. The study does not include mineralogical analysis, particle-size characterization, detailed geological logging, sulfur analysis, or controlled tracking of individual coal batches from seam to belt. These measurements would be needed to identify the physical mechanism responsible for the observed belt enrichment in ash.

The findings nevertheless provide a clear basis for further sampling. A larger program could collect repeated time-resolved increments from the same seam and corresponding conveyor stream, record geological and operational conditions, and use a variance-component framework to separate geological, sampling and analytical contributions. Such work would establish whether the G9-to-G11 difference observed here is persistent or specific to the sampled period.

V. CONCLUSIONS

This study demonstrates clear sampling-source-dependent variability in routine coal-quality parameters at Sharda Underground Mine. Drill and seam samples were closely similar, with mean GCVs of 4651.18 and 4623.04 kcal/kg and G9 classification. Belt samples, in contrast, averaged 43.14% ash, 30.20% fixed carbon and 4116.68 kcal/kg GCV and were consistently classified as G11. The belt samples therefore differed from drill samples by approximately 9.02 percentage points in ash and 534.50 kcal/kg in GCV. The observed pattern is consistent with the established influence of mineral matter on coal energy value, although the present dataset cannot determine the specific mechanism producing the higher belt ash. The main implication is methodological and practical: coal quality reported from one sampling point should not automatically be assumed to represent coal at another stage of the mining and handling system. Representative sampling of the population relevant to the intended quality decision is essential, particularly where GCV-based grading is involved. The present results provide a focused mine-level case study supporting more systematic, time-resolved investigation of sampling-source variability in Central Indian underground coal mines.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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