Integrated Multiscale Petrographical, Geochemical, Tectonic, and Spectroscopic Study of Bokaro Basin Coals: Implications for Coal Genesis, Utilization Potential, and Comparative Chemical Evolution

Abstract

This study presents a comprehensive investigation of the coal-bearing formations in the Bokaro Basin, Eastern India, focusing on integrated petrographic, geochemical, tectonic deformation, and spectroscopic analyses. The primary goal is to understand the evolution of the basin, the genesis of coal, trends in coalification, and the rank-dependent physicochemical behavior of coals, and to predict the appropriate utilization of coal from the Bokaro basin.

The research adopts a multidisciplinary approach, which combines the examination of basin-scale architecture, the reconstruction of depositional environments, the analysis of paleoclimate, and the dynamics of hydro-ecosystems, along with detailed characterization of coal and its potential uses. A comparative framework is employed to contextualize the Bokaro coals within the broader landscape of coal occurrences and distributions, as well as the coalification, deformation, and physicochemical evolution of coals throughout India.

The study presents a systematic, multi-scale framework for conducting a comprehensive geological and coal-based investigation. It begins with a literature review to identify research gaps, leading to the formulation of clear objectives. This is followed by an experimental and analytical plan, evaluation of results, conclusions, outcomes, and a proposed way forward, which collectively represent the progression of the research. The core of the study is structured around the scale of observation, beginning with the field area and expanding from regional to atomic levels. At the regional scale, reconnaissance surveys are conducted, including geological mapping using ArcGIS and GSI data, as well as detailed fieldwork and sampling. The megascopic scale focuses on field-based investigations, encompassing general geology, tectonic studies, and sedimentological signatures. Moving to the macroscopic scale, hand-specimen studies emphasize the characterization of macro lithotypes and natural deformation features. At the microscopic scale, laboratory analyses such as geochemistry, maceral analysis, mineral analysis, and micro-tectonic studies are performed. Lastly, the sub-microscopic scale investigates chemical structures,

functional groups, mineral identification, and pore characteristics. Overall, this framework integrates field, laboratory, and analytical approaches across multiple spatial scales to achieve a comprehensive understanding of basin architecture, depositional processes, coal characteristics, and their geological significance.

The research was meticulously designed to explore the past, present, and future of coal in the Bokaro Basin. It encompasses an examination of basin evolution, sedimentation, paleoclimate, and peat-forming environments (past); assesses the utilization potential of coal along with a thorough geochemical, petrographic, deformation, and spectroscopic characterization (present); and considers utilization predictions, forthcoming research directions, and implications (future). Additionally, coal samples of varying rank and deformation states from different Indian coal basins and geological ages were analyzed to enhance the study's depth and reliability.

The study begins with comprehensive fieldwork that encompasses field validation, tectonics, physical geology, sedimentology, and systematic pillar sampling of the working coal seams, as well as sporadic sampling of other associated rock types. The collected samples are then meticulously packed and transported to the laboratory. Laboratory analysis commences with the identification of macro-lithotypes, followed by thorough sample preparation. The prepared samples are analyzed using a combination of geological, petrographic, and geochemical techniques. These include proximate and ultimate analyses, micropetrography, spectroscopy, maturation studies, scanning electron microscopy (SEM), Rock-Eval pyrolysis, and Low-Pressure Gas Adsorption (LPGA), as well as palynological investigations. The integrated results are used to characterize and classify the coal by rank, grade, type, and deformation, and to assess its potential for various uses, such as thermal applications, coking, hydrocarbon source rock, and hydrocarbon potential. Furthermore, the study aims to reconstruct the paleo-depositional environment, considering factors such as paleoclimate, salinity, tectonic setting, water-table conditions, redox state, and paleoecology.

Genesis:

The Gondwana basins of India contain a record of approximately 200 million years of siliciclastic deposits and are renowned for their extensive coal reserves, which account for nearly 99% of the country's total coal resources. These basins are predominantly situated in the central and eastern regions of India and are characterized by isolated yet linearly disposed basins within the Gondwana

rift systems. One such basin is the Bokaro Basin, located in the Damodar River valley. It is an east-west-trending linear basin divided into two nearly equal halves by a significant highland known as Lugu Hill. The study included fieldwork and sample collection from both the West and East Bokaro sub-basins. The Bokaro Basin, along with its neighboring basins, has a long-standing history of systematic coal mining. It primarily supplies coal for thermal power plants and semi-coking coal to the steel industry for the production of metallurgical coke. However, a thorough assessment of coal quality in several seams has yet to be conducted. The Barakar Formation, the main coal-producing geological unit of this basin, was previously thought to be a fluvio-lacustrine deposit because of the absence of marine fossils. Recent studies, however, have cast doubt on this interpretation by reporting intermittent marine signatures from various Gondwana basins. So far, the verification of this estimate for the Bokaro Basin has not been completed. This study aims to address the unresolved question of marine influence during the deposition of the Barakar Formation in the West Bokaro Basin, which lies along a potential eastern marine transgression pathway linked to the Tethys Sea during the Early Permian. The presence of plant impressions on bedding planes, ichnofossils, alternating light and dark laminae in associated shale beds, and heterolithic units suggests fluctuating yet ecologically productive conditions. The preliminary indicators observed during fieldwork have prompted the need for a comprehensive integrated multi-proxy study. This study will combine organic petrography, palynology, and geochemistry to better understand the paleoclimatic conditions, paleoecology, and hydrodynamic regime during peat accumulation in the Bokaro Basin during the Early Permian.

The influence of tectonics on coal maturation has not been previously examined in India. Field and laboratory investigations conducted in the tectonically disturbed areas of the Bokaro Basin revealed a significant impact of tectonics on coal formation. However, because of the lack of a standardized classification scheme in India, an initial classification framework was developed through a thorough review of the existing literature. To address this gap, coal samples were analyzed from both tectonically less disturbed areas (Meghalaya) and deliberately deformed regions (Kalakot, Jammu). This led to the creation and validation of a new deformation classification chart and a comprehensive assessment of the tectonic controls on coalification.

While the processes of coalification and rank advancement under elevated pressure and temperature are well established, the molecular-level changes occurring during these transitions

remain poorly understood. To fill this knowledge gap, spectroscopic experiments, specifically Raman spectroscopy, were performed on coals of varying ranks to identify shifts in carbon bonding. The findings reveal systematic variations in the sp^2/sp^3 carbon ratio, an increase in aromaticity, and a decrease in structural disorder as coal rank increases.

The study places significant emphasis on the evolution of coal surface chemistry across various coal ranks and the implications for microstructure, rank enhancement, and potential utilization. It further investigates the rank-dependent amphiphilicity of coal, drawing correlations between surface wettability, contact angle measurements, and spectroscopic signatures - particularly X-Ray Photoelectron Spectroscopy - with combustion behavior and the effectiveness of beneficiation. A comparative evaluation of different coal ranks yields new insights into the transition from hydrophilic to hydrophobic characteristics during coalification. Additionally, a new formula has been introduced to quantify hydrophobicity based on XP spectroscopic data.

Our findings demonstrate a dynamic depositional environment controlled by tidal, wave, and fluvial interactions. Geochemical proxies such as CaO/MgO, Sr/Ba, and Th/U ratios, along with MgO and Al_2O_3 trends, reveal fluctuating paleo-salinity conditions ranging from brackish to marine. The presence of dolomite, siderite, limited pyrite, and alginite macerals further confirms episodic marine influence during peat formation. Sedimentological data, including tidal bundles, coarsening-upward sequences, and wave-ripple-tidalite associations, suggest deposition in supratidal to subtidal settings within a coastal lagoon or salt marsh system. This study confirms that the upper Barakar Formation in the West Bokaro Basin records at least two phases of marine transgression, separated by regressive phases marked by cross-bedded coarse sandstone units. These transgressions precede the previously documented marine flooding of the overlying Barren Measures Formation, implying that marginal marine conditions developed earlier in this basin than previously thought. This research refines the regional paleoenvironmental model of the Indian Gondwana and highlights the importance of multi-proxy approaches in reconstructing complex depositional histories.

Integrated geochemical, palynological, and petrographic analyses collectively suggest that peat accumulation in the Bokaro Basin occurred under a humid, warm-to-cooler subtropical-tropical paleoclimate during the Early Permian. Evidence of intense chemical weathering, prolonged interaction with meteoric water, and increasing chemical maturity indicates high rainfall and

humidity. Additionally, palynofloral assemblages predominantly composed of Glossopteridales further support the presence of abundant rainfall and swampy conditions. Petrographic indices reinforce the notion of mesotrophic to ombrotrophic peat-forming environments, emphasizing a continuously wet, vegetated landscape that was conducive to coal formation.

The Bokaro Basin hosted a dynamic hydro-ecosystem influenced by cyclic marine incursions, seasonal freshwater influx, and tide-dominated marginal marine conditions. Rainwater and nutrient-rich groundwater sustained moist, nutrient-enhanced swamps with fluctuating water depths, leading to alternating oxic–anoxic conditions and periodic sediment reworking during coal formation. These settings supported diverse vegetation, including aquatic plants, herbs, and algae within localized microenvironments, comparable to modern analogues such as the Sundarbans Delta and southern Florida swamp forests.

The Barakar Formation of the Bokaro Basin represents sedimentation in a mixed fluvial-coastal swamp system within a tectonically stable cratonic environment. Geochemical indicators reveal periodic flooding events that occasionally introduced oxygenated waters into the forested swamps. In contrast, consistent weathering and sediment recycling indicate a high level of compositional maturity and a secondary sedimentation cycle. The predominance of detrital components over authigenic ones signifies significant mechanical sediment transport from surrounding uplands, where fluvial processes were instrumental in shaping the depositional architecture and promoting coal accumulation, all within a context of overall tectonic stability accompanied by variable sediment influx.

Classification and Utilization:

While both East and West Bokaro basin coals are classified as medium volatile bituminous, East Bokaro coals demonstrate a higher rank due to the greater burial depth of the Karo Seam and increased lithostatic pressure. Petrographic analyses reveal that coal from both regions is rich in reactive macerals, making them suitable for metallurgical applications. However, the elevated ash content limits their classification as Prime Coking Coal. According to the Government of India standards, West Bokaro coals are primarily categorized as Washery Grade–I coking coal, whereas East Bokaro coals are mainly classified as Washery Grade–III coking coal, indicating minor variations in quality and beneficiation potential between the two coalfields. Both types correspond to Kerogen Type III, suggesting gas-prone properties, and are also favorable for gasification,

particularly in the East Bokaro region. Consequently, using these coals exclusively for power generation would result in underutilizing their higher economic and industrial value.

Overall, the findings provide a comprehensive understanding of coal formation and evolution in the Bokaro Basin, underline significant scientific outcomes relevant to coal utilization and beneficiation, and suggest future research directions focused on advanced characterization, cleaner coal technologies, and basin-scale resource optimization.

Keywords: Organic-Petrography, Bokaro Basin, Coal Utilization, Raman Spectroscopy, Paleoclimate.

Research Publication:

Serial	Title	Journal	Status
1	**Srivastava, M.K**., Vikram, K., Kishor, K**.**, Singh, A. K. (2025). Rank-Dependent Amphiphilicity of Coal: Insights into Combustion and Beneficiation Mechanisms. . https://doi.org/10.1021/acsomega.5c03877	*ACS Omega*	Published
2	**Srivastava, M.K**., Vikram, K., Kishor, K**.**, Singh, A. K., Mukherjee, S., & Singh, R. K. (2026). Unraveling coalification dynamics: A comprehensive spectroscopic study on the chemical and microstructural evolution from lignite to semi-anthracite. , 345, 126765. https://doi.org/10.1016/j.saa.2025.126765	*Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*	Published
3	**Srivastava, M.K**., Kishor, K**.,** Singh, A.K., Kumar, A., Mustapha, K.A., Saxena, A., 2025. Multi-analytical assessment of shale gas potential in the West Bokaro Basin, India: A clean energy prospect. 6, 100434. https://doi.org/10.1016/j.engeos.2025.100434	*Energy Geoscience*	Published
4	**Srivastava, M. K**., Kishor, K., Singh, A. K., Mukherjee, S., & Bharti, S. K. (2024): Tectonically Deformed Coal: Focus on Microstructures & Implications for Basin Evolution. 107223. https://doi.org/10.1016/j.marpetgeo.2024.107223	*Marine and Petroleum Geology*,	Published
5	**Srivastava, M. K**., Kishor, K., & Singh, A. K. (2024): A comprehensive petrochemical study of coals of Jaintia Hills: unveiling their industrial applicability and potential as	*International Journal of Coal*	Published

	hydrocarbon source rocks. , *00*(00), 1–15. https://doi.org/10.1080/19392699.2024.2353130	*Preparation and Utilization*	
6	**Srivastava, M. K.,** Kishor, K., Nath, M., & Singh, A. K. (2024). Inorganic geochemical attributes of Jaintia Hills coals, India: Implications for paleo-depositional conditions. , *51*(3), 100227. https://doi.org/10.1016/j.kjs.2024.100227	*Kuwait Journal of Science*	Published
7	**Srivastava, M. K.,** Kishor, K, Singh, A. K, Bharti, S. K., and Mukherjee, S. Study of Coal-Bearing Heterolithic Units for Reconstructing 2 Marine Pathways in the Eastern Gondwana Basin, India	*Geological Journal*	Accepted