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Characteristics variability of coals from Sumatera, Kalimantan, and Sulawesi: An insight from statistical and clustering analysis

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ABSTRACT. Indonesia has a complex geological structure with coal potential dominated by 3 main islands: Sumatra (SMS), Kalimantan (KS), and Sulawesi (SLS). The characteristics of coal from these three islands are not well-defined. This research aims to reveal the significant factors and differences in Sumatra, Kalimantan, and Sulawesi coals. We compare the results of proximate analysis (total moisture, moisture, volatile matter, fixed carbon), total sulfur, calories, specific gravity, Hardgrove grindability index (HGI), ultimate analysis (C, H, N, O, S), and coal ash analysis of coal samples from the three areas. We further process the data using cluster and principal component analyses (PCA) to enhance characteristics variabilities. The 55 coal samples from the three islands were divided into 9 main clusters with 50% similarity. Kalimantan coals are characteristically high in TiO_2, Al_2O_3, Na_2O, carbon, and nitrogen. Sumatra coals show high Total Moisture (TM), Moisture (M), MnO, CaO, MgO, Fe_2O_2, and SO_3. They also indicate the slight influence of HGI and Total Sulfur (TS). Meanwhile, Sulawesi coals show wider variability and complex characteristics and are most elevated in calorific value. Our findings suggest that the differences in coal characteristics are highly influenced by the different geological settings of these three islands.

Keywords: Coal · Statistics · Indonesia.

1 INTRODUCTION

Coal is a major player in world energy generation, and it is still being utilized and developed today, including in Indonesia (Arif, 2014). Based on coal potential data, the world has total coal reserves reaching 860.938 million tons (Thomas, 2013) up to 1.074.108 million tons, where 42.8% of these reserves are in Asia (BP, 2021). Indonesia is one of the countries with a large coal potential. It is recorded that Indonesia has 105.187 million tons of coal resources and 21.131 million tons of coal reserves (Stanford, 2013). Meanwhile, data released by the Center for Mineral, Coal, and Geothermal Resources (CMCGR) shows that in 2023, Indonesia has coal potential, reaching 98.545 million tons of resources and 33.864 million tons of reserves. In recent years, Indonesia and other countries have aimed to follow clean energy regulations and achieve net zero emissions (Atteridge *et al.*, 2018). However, world coal production is predicted to increase 8% 2022 to 8.634 million tons. Apart from that, Indonesia, as one of the largest producers, is expected to increase coal production and reach peak production in 2023 at 695 million tons (IEA, 2023).

Indonesia has 60 sedimentary basins with coal potential distributed over 2 main islands. These islands are Kalimantan and Sumatra, and there is a little coal potential also found in Sulawesi, Papua, and Java (Standford, 2013; IEA, 2023; PSDMBP, 2023). Coal in Indonesia is dom-

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inated by lignite and sub-bituminous rank, but there is also bituminous and anthracite coal. All coal in Indonesia has Paleogene to Neogene age (Standford, 2013). Increasing the use and utilization of coal in Indonesia will indirectly improve the country's economy. This happens because the use of coal is closely related to the main industrial sources in Indonesia, one of which is electricity (Kim & Yoo, 2016).

Indonesia has a complex geological structure because it is located on the boundary of 3 world's main plates: the Eurasian, Pacific, and Indo-Australian (Hall, 2002; Metcalfe, 2011; Metcalfe, 2013). A large part of Indonesia belongs to Sundaland, representing a significant part of the Earth's continental shelf. Indonesia was formed by the Gondwana microcontinent drifting, which has experienced convergence, collision, and accretion to create an archipelago with sutures as the boundaries between the microcontinents (Metcalfe, 2011; Metcalfe, 2013). The main process that influenced Indonesia's geological conditions is the fragment came along with the opening of the Ceno-Tethys Sea, which brought parts of Kalimantan, Java, and Sulawesi (Hall, 2002; Metcalfe, 2011; Metcalfe, 2013).

Prior research on Indonesian coals mainly focuses on coal development, characteristics, and potential in general (Amijaya and Littke, 2005; Friederich *et al.*, 2016; Friederich & Leeuwen, 2017), but comparative studies on the characteristics variability of these coals are not well defined. This research aims to compare characteristics variability in Sumatra, Kalimantan, and Sulawesi coals to provide a better target market assessment in Indonesia (Figure 1).

2 METHODOLOGY

We collected 55 samples: 21 from South Kalimantan province, 22 from South Sulawesi province, and 12 from South Sumatra province. The coal samples were taken randomly in a ply-by-ply sampling at locations where coal was found on these three islands. A 3 kg of coal samples were taken at each sampling point and then analyzed for proximate analysis (total moisture, moisture, volatile matter, fixed carbon), total sulfur, calories, specific gravity, HGI, ultimate analysis (C, H, N, O, S), and coal ash analysis (Rasheed *et al.*, 2015; Putra *et al.*, 2018; Sardi *et al.*, 2023). Coal samples were tested at the Center for Mineral, Coal, and Geothermal Resources laboratory.

We then use the laboratory analytical results as parameters for statistical analysis, including proximate analysis (total moisture, moisture, volatile matter, fixed carbon), total sulfur, calories, specific gravity, HGI, ultimate analysis (C, H, N, O, S), and coal ash analysis. The statistical analysis used in this study includes principal component analysis (PCA) and cluster analysis.

Principal Component Analysis is carried out to determine the closeness of samples and coal parameters by reducing coal characteristic variables from laboratory tests (Jolliffe & Cadima, 2016; Tharwat, 2016). The data reduction stages in PCA include Data Standardization Calculation with formula (Equation 1), Covariance Calculation with formula (Equation 2), Eigenvalue and Eigenvector Calculation of the covariance matrix as the main component with formula (Equation 4), Data Projection to the Main Component through eigenvector, and finally Component Selection is carried out based on the size of the eigenvalue. The component with the largest eigenvalue contains the most information (variance) (James *et al.*, 2013).

$$Z = \frac{X - \mu}{\sigma} \tag{1}$$

$$C = \frac{1}{n-1} Z^T Z \tag{2}$$

$$Cv = \lambda v \tag{3}$$

$$Zn = Zv \tag{4}$$

With $CapZ$ = Standardized data; X = Matrix data; n = Sampel data; μ = Mean data; σ = Standard deviation; C = Covariance; Z^T = Transpose Z; v = Eigenvector; λ = Eigenvalue; Zn = Principal component data.

Cluster Analysis was carried out to see the closeness of the samples by calculating the similarity in each coal sample. Cluster analysis was carried out using the hierarchical clustering method with an agglomerative (bottom-up) approach to see the similarity of the samples (Lee, 1981; Murtagh & Contreras, 2012; Stahl & Sallis, 2012; Kandemir, 2016). The purpose is to

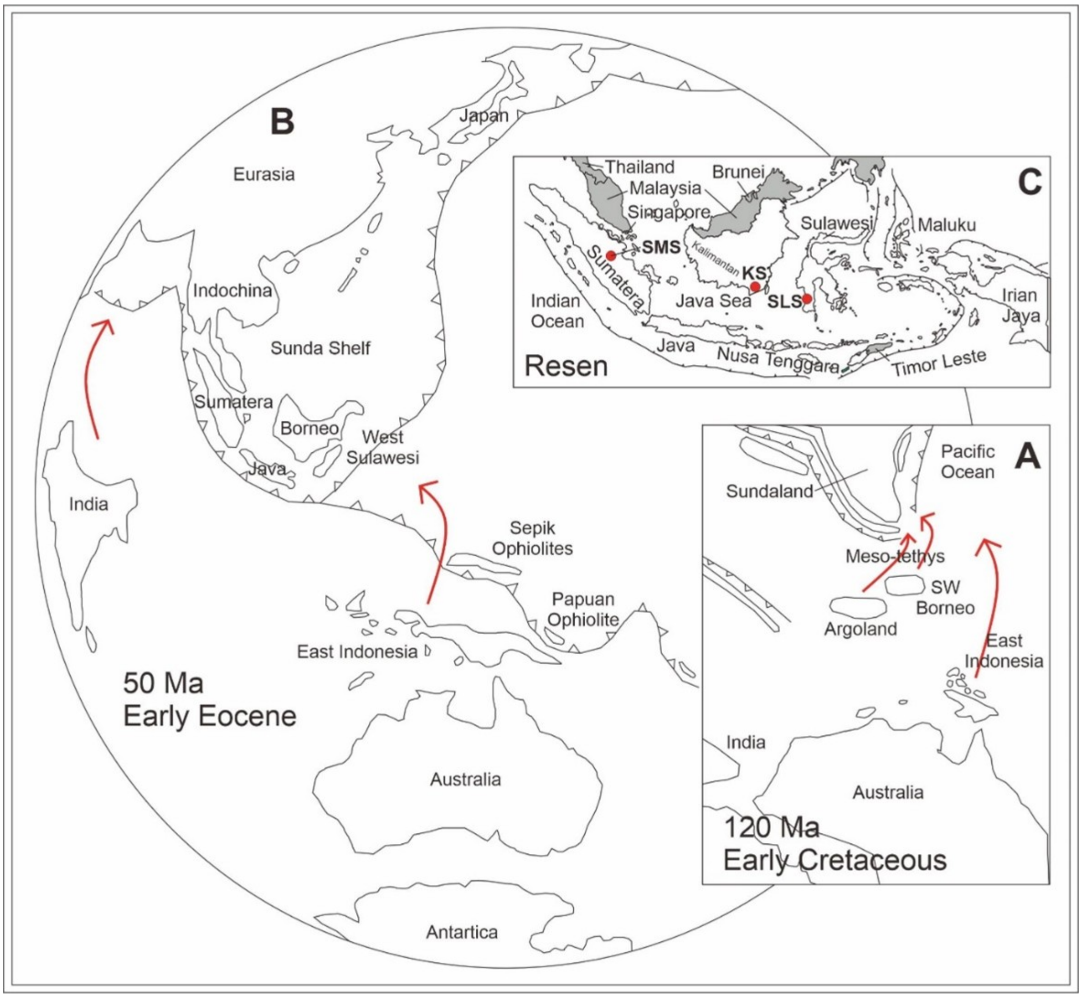

FIGURE 1. Location of research area: (a) Early Cretaceous geological setting shows the movement of Argoland and SW Borneo microcontinents to Sundaland (Metcalfe, 2011; Metcalfe, 2013); (b) The Early Eocene geological setting shows the movement of Indian and Eastern Indonesian plates into Eurasia (Hall, 2002; Hall, 2012); (c) Research sample locations on Sumatra, Kalimantan and Sulawesi.

maximize the similarity between objects within a cluster and minimize the similarity between objects in different clusters.

The clustering stage in this analysis includes the formation of individual clusters, which are then combined based on distance into one cluster. This process is repeated until all data is combined in one cluster or until a certain number of clusters is reached. The distance measurement method used in this study is Average Linkage, which measures the distance between two clusters and the average distance between all points from different clusters. The results of this analysis are represented in the form of a dendrogram, a tree diagram that describes how clusters are combined based on their proximity (Kaufman & Rousseeuw, 2009).

Principal Component Analysis (PCA) and cluster analysis were completed on data processing applications, including Minitab and SPSS. After the study, the results were validated by looking at the scree plot, data visualization, and comparative analysis to ensure that the PCA and cluster analysis results were good.

3 RESULTS AND DISCUSSION

Kalimantan coal in this study is from the Tanjung Formation and Warukin Formation of Eocene - Miocene age with a fluvial to shallow marine depositional environment in some parts (Zamroni *et al.*, 2020; Fikri *et al.*, 2022). Sulawesi coal samples were from the Eocene Malawa Formation with a fluvial depositional environment. (Sukamto, 1982; Wilson and Moss, 1999). Meanwhile, the Sumatra coal is from the Lakat Formation, which is Oligocene – Miocene age

(Fiqih *et al.*, 2024). The coal from these three islands generally has equivalent age and depositional environment characteristics (Heryanto, 2006).

Results from laboratory analysis showed that the research samples had a variety of proximate analyses, total sulfur, calories, specific gravity, HGI, ultimate analysis, and coal ash analysis values (Table 1). From the results of laboratory analysis, it can be seen that there are several differences. Kalimantan coal tends to have higher volatile matter (VM), fixed carbon (FC), and calories (CV) when compared to Sulawesi and Sumatra coal. When viewed from the ash parameter, Sulawesi coal has a high value, reaching 77.93. This difference is also in line with the results of ultimate analysis, especially in the elements C and O. Table 1 shows that Kalimantan coal has an increase in the element C and a decrease in the element O. Other parameters do not show significant differences between the three islands.

Cluster analysis shows 9 main clusters with similarity parameters reaching 50%. In general, coal samples in the same area show the same characteristics. At the same time, coal on different islands has coal characteristics that tend to be different. However, several samples of each island also showed anomalous coal characteristics, which will be explained in the next section. Therefore, cluster analysis results show that this anomaly separates several samples into their clusters. The following are the results of the analysis of each coal cluster (Figure 2).

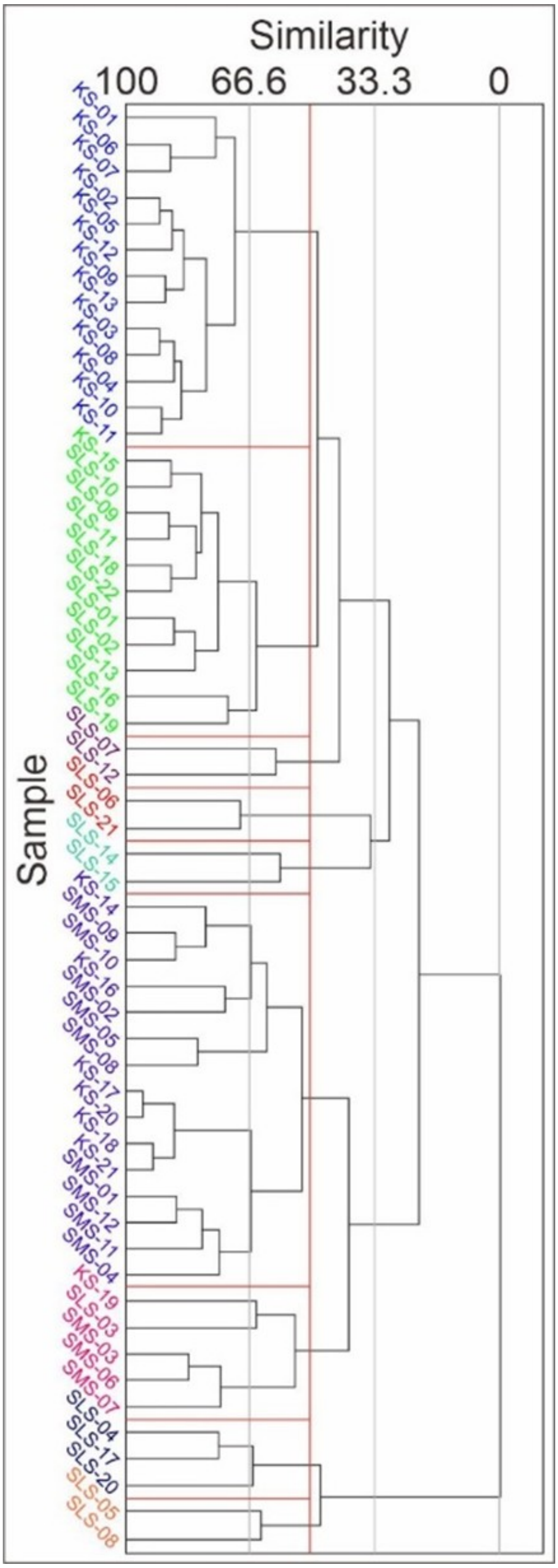

FIGURE 2. The coal cluster diagram shows 9 main clusters with 50% similarity, which use a hierarchical clustering method with an agglomerative (bottom-up) approach.

1. Cluster 1

Kalimantan coal samples mostly dominate the first cluster. This cluster is interpreted as the main cluster of Kalimantan Island. The samples from this cluster mainly show high TiO_2, Al_2O_3, Na_2O, C and N content. Compared to the other clusters, these coals show elevated calories.

2. Cluster 2

The second cluster is mainly dominated by Sulawesi coal samples and one Kalimantan sample (KS-15). This cluster is interpreted as the main cluster of Sulawesi Island, which does not show any particular characteristics. In a closer look, however, a slight influence of high content from Ash, SG, VM, elements H, Rv, K_2O,

TABLE 1. Laboratory analysis results of coal samples from Kalimantan, Sulawesi and Sumatra.

Parameter	Kalimantan	Sulawesi	Sumatra	Parameter	Kalimantan	Sulawesi	Sumatra
TM (%ar)	4.88 - 37.57	5.41 - 27.76	49.29 - 60.35	SiO_2 (%)	1.6 - 52.54	10.61 - 73.29	4.04 - 66.18
M (%adb)	3.66 - 11.01	1.65 - 11.41	10.05 - 13.40	Al_2O_3 (%)	0.98 - 44.39	7.44 - 31.19	4.15 - 32.5
VM (%adb)	41.48 - 50.73	8.75 - 49.97	28.74 - 49.15	Fe_2O_3 (%)	1.72 - 59.48	6.09 - 55.76	5.01 - 54.63
FC (%adb)	38.53 - 48.74	7.89 - 62.46	20.37 - 35.13	CaO (%)	1.13 - 30.06	0.60 - 25.11	0.24 - 27.39
Ash (%adb)	1.40 - 10.12	2.73 - 77.93	5.05 - 40.84	MgO (%)	0.28 - 21.37	0.62 - 4.88	0.54 - 5.33
TS (%adb)	0.10 - 2.57	0.23 - 9.63	0.5 - 5.07	Na_2O (%)	0.35 - 3.55	0.18 - 2.21	0.49 - 1.31
CV (cal/g; %adb)	5685 - 7489	1359 - 7759	2779 - 5585	K_2O (%)	0.10 - 1.23	0.81 - 3.70	0.33 - 0.93
SG	1.26 - 1.39	1.15 - 2.73	1.36 - 1.67	TiO_2 (%)	0.20 - 7.47	0 - 1.43	0.35 - 1.95
HGI	36 - 69	26 - 103	45.45 - 69.63	MnO (%)	0 - 0.89	0.01 - 0.07	0.01 - 1.82
C (%daf)	70.33 - 81.62	40.59 - 90.27	56.74 - 71.42	P_2O_5 (%)	0.01 - 0.88	0.06 - 9.86	0.01 - 0.14
H (%daf)	4.72 - 6.60	3.04 - 8.23	4.41 - 5.35	SO_3 (%)	0.07 - 7.39	0.23 - 41.43	0 - 27.52
N (%daf)	0.93 - 1.80	0.83 - 1.72	0.5 - 1.09	H_2O (%)	0.12 - 4.24	0 - 2.09	0.1 - 1.07
O (%daf)	9.81 - 22.82	0.58 - 49.63	20.5 - 35.36	HD (%)	0.16 - 3.20	0.84 - 27.33	0.07 - 1.18
S (%daf)	0.12 - 2.88	0.64 - 15.34	0.63 - 8.92	Rv (%)	0.32 - 0.59	0.29 - 4.74	0.23 - 0.31

P_2O_5, and H_2O are observed in samples from this cluster.

3. Cluster 3

The third cluster is the SLS-07 and SLS-12 samples from Sulawesi, which are separated anomalously from cluster 2. The two samples from this cluster show anomalously high calorific values, fixed carbon, and carbon compared to other cluster coals.

4. Cluster 4

The fourth cluster is SLS-06 and SLS-21 samples from Sulawesi, separated anomalously from cluster 2. Compared to the cluster 2, the samples from this cluster show anomalously high SiO_2 and H.

5. Cluster 5

The fifth cluster is the SLS-14 and SLS-15 samples, separated anomalously from cluster 2. Compared to the cluster 2, the samples from this cluster show anomalously high P_2O_5 and H elements.

6. Cluster 6

The sixth cluster is mainly a mixture of coal samples from Sumatra and Kalimantan. But it is still dominated by coal originating from Sumatra. This cluster is interpreted as the main cluster of Sumatra Island because it is dominated by samples originating from the island of Sumatra. The samples from these clusters are high in TM, M, MnO, CaO, MgO, Fe_2O_3, and SO_3 contents.

7. Cluster 7

The seventh cluster is KS-19, SLS-03, SMS-03, SMS-06 and SMS-07 samples. This cluster is interpreted as an additional cluster for Sumatra Island, which shows anomalies accompanied by several samples from Kalimantan and Sulawesi. Meanwhile, the main characteristic seen from this cluster is the high content of HGI, TS, O, and S elements. This analysis shows that coal originating from Sumatra slightly increases HGI, TS, O, and S elements. However, this increase also occurs in 1 coal sample in Kalimantan and Sulawesi.

8. Cluster 8

The eighth cluster consists of samples SLS-04, SLS-17, and SLS-20. This cluster is interpreted as an additional cluster on Sulawesi Island, which shows an anomaly. Meanwhile, the main characteristic seen from this cluster is the high content of Ash, SG, Rv, and K_2O. From this analysis, coal originating from Sulawesi shows a slight increase in Ash, SG, Rv, and K_2O. However, this increase is not as significant as the main cluster in Sulawesi.

9. Cluster 9

The ninth cluster is the SLS-05 and SLS-08 samples. This cluster is interpreted as an additional cluster on the island of Sulawesi, which shows an anomaly. Meanwhile, the main characteristic seen from this cluster is the very high content of Ash and SG. From this analysis, coal originating from Sulawesi shows a slight increase in Ash and SG. However, this increase is not as significant as the main cluster in Sulawesi.

Results from cluster analysis show that there are differences in the characteristics of coal on these three islands. This is also confirmed by the results from PCA analysis, which shows that samples are clustered on each island even though some samples have anomalies. The cluster analysis and PCA analysis results indicate fundamental differences in coal on Kalimantan, Sumatra, and Sulawesi islands (Figure 3). This also shows that the results of cluster analysis and PCA in this study can be validated well.

Kalimantan Island has coal with the main characteristics consisting of TiO_2, Al_2O_3, Na_2O, C elements, and N elements, as well as support in the form of calorific value. On Sulawesi island, coal does not have main significant characteristics, but there are supporting attributes in the form of increased Ash, SG, VM, elements H, Rv, K_2O, P_2O_2, FC, C, SiO_2, Ash, SG, and H_2O. Meanwhile, on Sumatra island, coal has the main characteristics of TM, M, MnO, CaO, MgO, Fe_2O_3, and SO_3, with supporting characteristics of HGI, TS, O elements, and S elements.

Coal will have different characteristics due to several factors. The initial process of coal formation is influenced by the source of material, depositional environment, climate, and hydrological conditions. Meanwhile, tectonic settings and processes related to other geological conditions occur at the end of the coalification process (Sun *et al.*, 2010). Besides that, geological processes related to age are closely related to increases in pressure and temperature, which will change coal's chemical and physical properties (Miller and Tillman, 2008). Hagelskamp *et al.* state that the characteristics of coal are closely related to geological conditions that occurred both during coalification and after the coal was formed.

From this explanation, it can be interpreted that the coal found in Kalimantan, Sulawesi, and Sumatra differs because these three islands have very different tectonic settings. This is because Indonesia is located on the boundary of three major plates, which causes this country to have complex geological conditions (Charlton, 2000; Metcalfe, 2011 & 2013). So, the coal formed on these three islands will have different sources and processes. Thus producing coal with other characteristics.

4 CONCLUSION

Indonesia has coal potential, which is dominated by 3 main islands, namely Sumatra (SMS), Kalimantan (KS), and Sulawesi (SLS). Fifty-five coal samples show that the coal on these three islands has different characteristics and can be divided into 9 clusters with 50% similarity.

Kalimantan Island has coal with increased TiO_2, Al_2O_3, and Na_2O oxides with carbon and nitrogen elements. Sumatra Island has coal with increased TM, M, MnO, CaO, MgO, Fe_2O_3, SO_3, and a slight influence of HGI and TS. Meanwhile, Sulawesi Island has coal with parameter complexity and increased calorific value. It is interpreted that the differences in coal characteristics are influenced by the past geological settings of these three islands.

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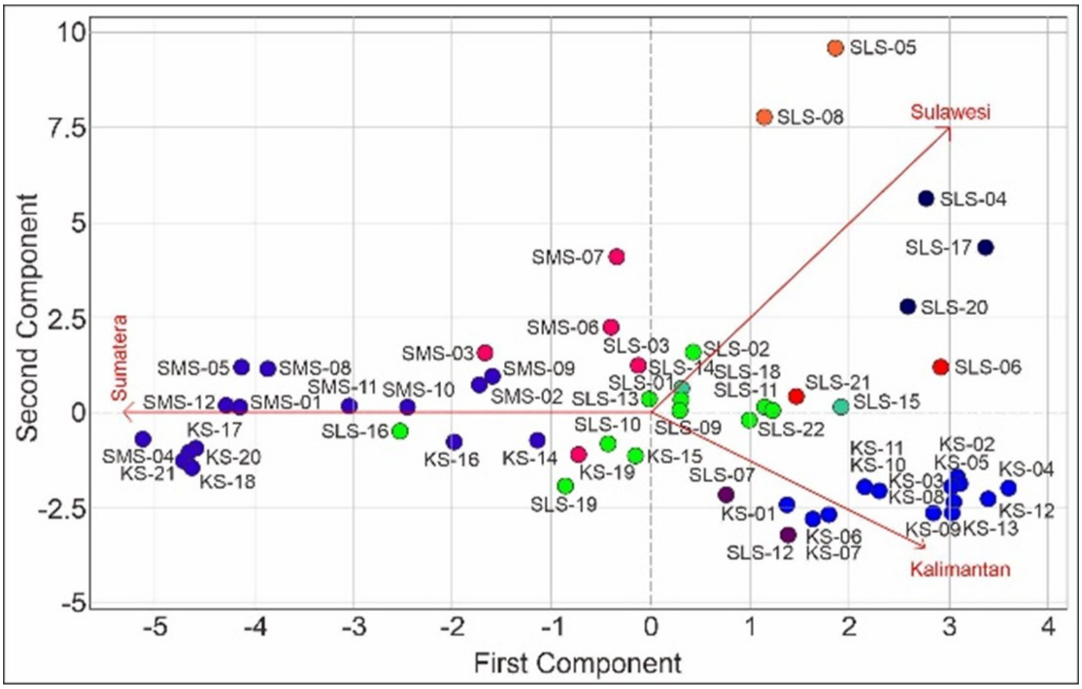

FIGURE 3. Principal component analysis (PCA) diagram of coal samples categorized based on coal cluster analysis. The optimum number of principle components from the scree plot is 2PC; Percent of variance PC1 = 25% PC2 = 23%.

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