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Original Research

Linking Coal Physicochemical Properties with NO_x Emissions in Lignite-Fired Power Plants: A Multivariate Analysis of Kosovo A and B

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Abstract

This study investigated the relationship between the physicochemical characteristics of lignite coal and nitrogen oxide (NO_x) emissions from the Kosova A and Kosova B thermal power plants during 2025. Monthly coal samples were analyzed for moisture, ash, total sulfur, organic sulfur, nitrogen content, calorific value, and higher heating value (HHV), while operational emission data were used to assess NO_x concentrations and calculated ENOx rates. The results showed clear seasonal variability in coal quality, indicating that lignite properties changed throughout the year and affected combustion behavior. Principal component analysis (PCA) revealed that two principal components explained approximately 89% of the total variance, with the first component mainly related to the energetic quality of coal and the second associated with moisture and chemical composition. Emission analysis demonstrated that NO_x concentrations remained high throughout the year, with Kosova B showing a greater contribution to the overall emission burden than Kosova A. Pearson correlation analysis showed that moisture, ash, and nitrogen were positively associated with NO_x and ENO_x, whereas calorific value and HHV were negatively correlated with emission indicators. These findings indicate that coal with lower energetic quality and higher non-combustible content tends to generate higher NO_x emissions. Overall, the study demonstrates that NO_x emissions in lignite-fired power plants are strongly influenced by the interaction between coal quality and combustion operating conditions, highlighting the importance of continuous fuel quality monitoring and combustion optimization for emission reduction.

Keywords: lignite, NO_x emissions, coal quality, thermal power plants

Introduction

Air pollution represents one of the most important environmental and health challenges at the global level, directly affecting quality of life and the functioning of natural ecosystems. Industrial activities and energy production from fossil fuels are considered among the main sources of atmospheric pollutants. Among these pollutants, nitrogen oxides (NO_x) occupy a special place due to their role in the formation of tropospheric ozone, photochemical smog, and acid rain, as well as

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because of their negative impacts on human health and the environment. Numerous studies have shown that prolonged exposure to NO_x is associated with respiratory and cardiovascular problems, while at the environmental level it contributes to ecosystem degradation and the acidification of soil and water [1-4].

Coal-fired power plants remain among the main contributors to NO_x emissions in many countries around the world. The coal combustion process takes place at high temperatures, favoring chemical reactions that lead to the formation of nitrogen oxides as a result of the oxidation of nitrogen present in the fuel and in the combustion air. According to studies conducted by Ding et al. and Rahman et al., the physicochemical characteristics of coal play a decisive role in the process of NO_x formation during combustion [5, 6].

Parameters such as moisture content, ash percentage, nitrogen content, and calorific value directly affect combustion temperature and the chemical processes that occur in industrial boilers. Along the same lines, more recent studies have shown that ash content, total moisture, and calorific value, together with operational parameters, are among the most influential variables in predicting NO_x emissions in power plants [7].

In the contemporary literature, numerous studies have been conducted to analyze the mechanisms of NO_x formation and the factors affecting their emissions in thermoelectric plants. Hong et al. analyzed combustion characteristics in pulverized coal boilers and demonstrated that combustion configuration and the use of low-emission burners can significantly reduce NO_x emissions [8].

Similarly, Ma et al. analyzed the co-combustion processes of coal and ammonia, showing that changes in fuel composition significantly affect the formation of nitrogen oxides during the combustion process [9]. These results support the idea that coal characterization and optimization of the combustion regime are two key elements for understanding and reducing NO_x emissions in coal-fired plants [8, 9].

In addition to experimental studies, recent literature has emphasized the importance of using advanced data analysis methods for monitoring and predicting atmospheric pollutant emissions. Models based on artificial intelligence and machine learning have increasingly been used to build predictive systems for NO_x emissions in industrial plants. Wu et al. developed a combined model that integrates physical knowledge of combustion processes with operational data analysis to improve the prediction of NO_x emissions in coal-fired power plants [10]. Further, He and Ding used algorithms based on Random Forest and Just-In-Time Learning to develop a predictive model for real-time monitoring of NO_x emissions in thermoelectric plants [11]. Deep learning methods have also found wide application in this field. Yin et al. proposed a model based on the CNN-LSTM architecture for predicting NO_x concentrations in coal-fired power plants, demonstrating that the combination of data analysis techniques and operational parameters can significantly improve the accuracy of predictive models [12]. So et al. used deep neural networks to predict SO_x and NO_x emissions in thermoelectric plants, showing that fuel characteristics and operational parameters are among the most important factors affecting the formation of atmospheric pollutants [13]. As a complement to this line of research, Wang et al. also reported that deep learning-based models can significantly increase the accuracy of NO_x prediction under dynamic combustion conditions [14].

Another important research direction is the monitoring of atmospheric emissions on a regional and global scale. Recent studies have used satellite data and advanced atmospheric models to analyze the spatial distribution of NO_x emissions from industrial and energy sources. Van der A et al. analyzed anthropogenic NO_x emissions in Europe using satellite data and identified coal-fired power plants as among the main sources of atmospheric pollution in the region. They demonstrated that NO_x emissions in Europe can be monitored independently from space, providing important support for emission inventories and the evaluation of environmental policies [15]. Reports of the European Environment Agency also emphasize that, despite the overall reductions in emissions during the last decade, large combustion plants continue to contribute significantly to air pollution in Europe [2, 16]. In Southeastern Europe, electricity generation remains largely dependent on lignite combustion, a fuel characterized by high moisture content and relatively low calorific value. In Kosovo, the Kosova A and Kosova B power plants constitute the main source of electricity production and at the same time one of the most important sources of atmospheric pollution in the country. Both facilities operate with pulverized lignite-fired boiler systems, where finely ground coal is combusted at high temperatures to produce steam for electricity generation. In such systems, NO_x formation is strongly influenced by combustion temperature, burner configuration, air–fuel mixing, residence time, excess oxygen conditions, and fuel nitrogen content. Older combustion technologies and conventional burner systems may contribute to higher NO_x formation compared with modern low-NO_x combustion systems.

Various studies have analyzed pollutant emissions from these plants and have shown that coal characteristics and combustion operating conditions directly affect atmospheric emission levels [17].

Institutional reporting for Kosovo underlines that compliance challenges of large combustion plants remain current and that the energy sector continues to play a major role in the country's air pollution profile [18]. A recent study on lignite-fired power plants in Kosovo analyzed sulfur dioxide emissions and highlighted the importance of coal characterization for assessing the environmental impacts of electricity generation. The results of this study show that fuel composition and quality play an important role in

determining the levels of atmospheric pollution from thermoelectric plants. However, despite the contribution of these studies to understanding the emission processes from lignite combustion, analyses that directly link the physicochemical characteristics of coal with actual nitrogen oxide (NOx) emissions from operating plants remain limited in the scientific literature, especially in the case of Kosovo [19]. Previous studies in Kosovo have mainly focused on general emission monitoring and environmental assessment of lignite-fired power plants. In contrast, this study investigates the direct relationship between lignite physicochemical properties and real NO_x emissions under operational conditions using integrated coal characterization and multivariate analysis.

For this reason, there is an important need for studies that combine laboratory analyses of coal quality with actual emission data from power plants. Such an approach can contribute to identifying the main factors affecting NO_x formation and to developing more effective strategies for the management of atmospheric pollution in the energy sector.

In this context, the aim of this study is to analyze the relationship between the physicochemical characteristics of coal and nitrogen oxide (NO_x) emissions in the Kosovo A and Kosovo B power plants during 2025. The study integrates laboratory data on coal composition with actual emission measurements from the power plant stacks and applies multivariate analysis to identify the key factors affecting NO_x formation. The results of this study are expected to contribute to a better understanding of atmospheric pollution processes in thermoelectric plants and to provide a scientific basis for the development of policies and strategies for emission reduction in the energy sector.

Experimental

Study Area

The study area comprises the KEK energy region in Kosovo, including the Kosovo A and Kosovo B thermal power plants as well as the municipality of Obiliq. The map was prepared in ArcMap by integrating vector layers with the "World Imagery" basemap from ArcGIS Online. Spatial data were harmonized using the KosovaREF coordinate system to ensure accuracy and consistency. The final map was exported in PNG format at 310 dpi (Fig. 1).

Coal Sampling and Laboratory Analysis

Coal samples were collected daily throughout 2025 during routine plant operation, while the monthly values used in this study were calculated as average values derived from the daily measurements in order to obtain a representative characterization of lignite quality for each monitoring period. The collected samples were subjected to laboratory analysis for the determination of key physicochemical parameters, including total moisture, ash content, total sulfur, organic sulfur, nitrogen content, and gross calorific value expressed as higher heating value (HHV).

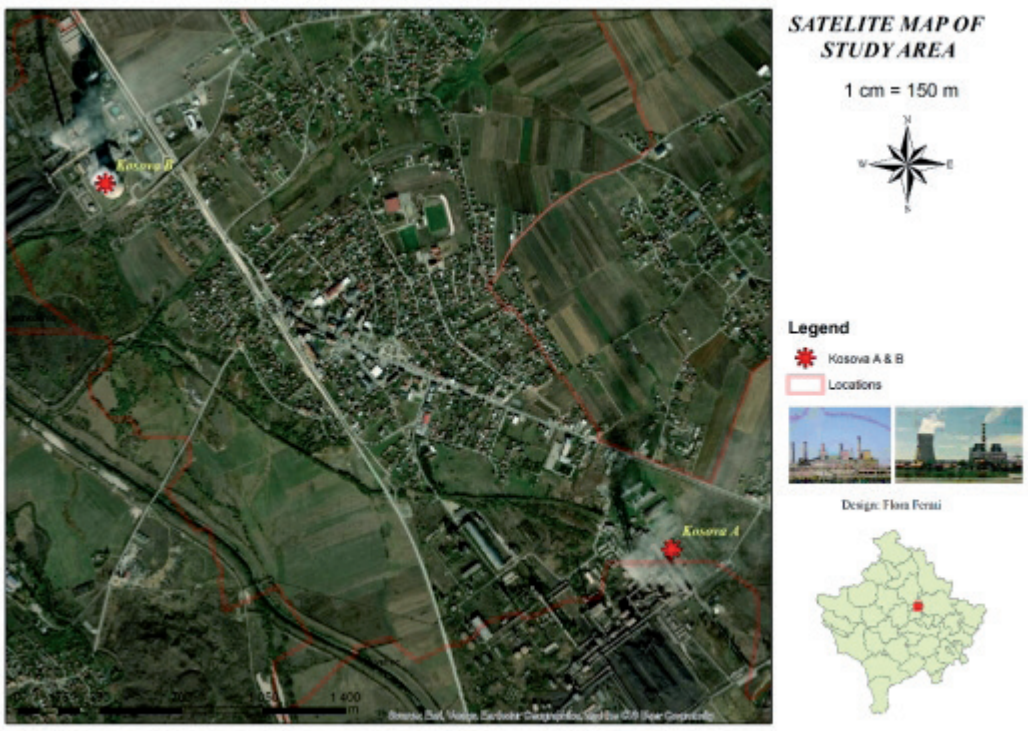


Fig. 1. Study area including Kosovo A and B power plants.

The analyses were performed in accordance with internationally recognized ASTM and ISO standards [20-25].

Total moisture was determined according to ASTM D3302/D3302M-22a [20], which is applicable to coal as sampled (as received). Ash content was determined according to ASTM D3174 [21]. Nitrogen content was measured according to ASTM D5373 using CHN elemental analysis [22].

Total sulfur was determined by high-temperature combustion with infrared detection according to ASTM D4239 [23]. Organic sulfur was determined according to ISO 157:1999, based on the distribution of sulfur forms in coal [24].

Gross calorific value was determined according to ISO 1928 using a bomb calorimeter [25], and the results were expressed as higher heating value (HHV). The monthly results of the physicochemical analyses of coal samples and monthly electricity generation data (MWh) are summarized in Table 1.

NO_x Measurement and Emission Calculation

NO_x concentrations were measured at the Kosovo A and Kosovo B thermal power plants using a Testo 350-XL flue gas analyzer, equipped with sensors for flue gas temperature and gaseous pollutant concentration. The instrument was used under operating conditions to obtain monthly NO_x concentration data from the stack gases.

The NO_x emission rate, expressed in kilograms per hour (kg h^{-1}), was calculated based on the measured concentrations of NO_x in the stack gases, the volumetric flow rate of the flue gases, the gas temperature, and the molecular weight of the respective pollutant. The equation applied in this study follows an internationally recognized standard methodology [26] and is presented in Equation (1).

$$E_i = \frac{C \cdot MW \cdot Q_{st} \cdot 3600}{\left[22.4 \cdot \left(\frac{T+273.15}{273.15}\right) \cdot 10^6\right]} \quad (1)$$

Where:
Ei – emissions of pollutant *i* (kg h^{-1});
C – concentration of the pollutant (ppm);
MW – molecular weight of the pollutant (kg $kmol^{-1}$);
Qst – volumetric flow rate of the stack gas under actual conditions (m^3 s^{-1});
3600 – conversion factor (seconds per hour);
T – gas sample temperature (K);
10^6 – conversion factor for ppm;
22.4 – molar volume of an ideal gas at standard temperature and pressure (0°C and 101.3 kPa) (m^3 $kmol^{-1}$).

The monthly NO_x concentrations and the corresponding calculated ENO_x values are presented in Table 2.

Statistical Analysis

Prior to principal component analysis (PCA), monthly coal-quality variables were standardized using z-scores. Statistical analyses were carried out using OriginPro 10.1 software. Pearson correlation coefficients were then computed to evaluate the relationships between coal physicochemical parameters and two emission indicators: combined NO_x concentration

Table 1. Monthly physicochemical characteristics of coal samples and corresponding electricity generation data (MWh) for the Kosovo A and Kosovo B power plants.

Month	Moisture [%]	Ash [%]	Total Sulfur [%]	Organic Sulfur [%]	Calorific Value (kcal/kg)	Higher Heating Value (HHV) (kJ/kg)	Nitrogen [%]	Electricity Generation (MWh) Kosova A	Electricity Generation (MWh) Kosova B
January	49.12	35.04	1.42	0.66	4480	18744	0.98	205511.3	421438
February	49.89	35.51	1.44	0.68	4460	18660	0.75	186934.1	356042
March	48.74	34.83	1.46	0.70	4520	18911	0.82	219466.3	406750
April	46.57	33.78	1.39	0.68	4650	19455	0.79	184814.9	246660
May	46.34	33.61	1.43	0.65	4621	19334	0.75	177853.1	217275
June	47.89	34.24	1.47	0.69	4610	19288	0.71	160467.3	194766
July	48.27	33.34	1.33	0.61	4574	19137	0.64	221063.5	199423
August	48.35	34.62	1.51	0.75	4528	18945	0.59	194404.2	243490
September	48.54	34.66	1.53	0.87	4502	18836	1.25	229506.2	250216
October	49.19	36.52	1.58	0.80	4478	18736	0.92	198993.6	382266
November	49.59	35.36	1.61	0.85	4325	18095	1.55	183198.6	387631
December	49.22	35.49	1.59	0.90	4332	18125	1.43	204668.1	364146

(Kosovo A+B) and ENO$_x$. Considering that the dataset included only 12 monthly observations, the correlation analysis was treated as exploratory and interpreted with caution, taking into account both effect size and process plausibility.

Results and Discussion

Coal Properties and Seasonal Variability

The analysis of the physicochemical parameters of coal during 2025 revealed a clear seasonal variation in fuel quality (Table 1). Moisture content ranged from 46.34% to 49.89%, ash content from 33.34% to 36.52%, total sulfur from 1.33% to 1.61%, and organic sulfur from 0.61% to 0.90%. At the same time, the calorific value and HHV varied from 4325 to 4650 kcal/kg and from 18095 to 19455 kJ/kg, respectively, whereas nitrogen content ranged from 0.59% to 1.55%. These fluctuations indicate that the coal used throughout the year was not homogeneous, but exhibited considerable variation in both composition and energy-related properties, with potential implications for combustion efficiency and the formation of pollutant emissions, particularly NO$_x$. In addition, the monthly electricity generation data of the Kosovo A and Kosovo B power plants presented in Table 1 indicate variations in operational load throughout the monitoring period, which may also have contributed to differences observed in NO$_x$ emission behavior.

PC1, which explained 76.00% of the total variance, represented the contrast between calorific properties and compositional parameters of coal. Higher heating value (HHV) and calorific value were positioned on the negative side of PC1, whereas organic sulfur, total sulfur, nitrogen, ash, and moisture content were located on the positive side of the component. This opposite orientation suggests an inverse relationship between fuel energy quality and the presence of sulfur-, ash-, and moisture-related characteristics. Coal samples with increased sulfur, ash, and moisture contents tended to exhibit lower calorific efficiency and reduced heating performance. PC2, accounting for 12.95% of the total variance, mainly differentiated samples according to sulfur- and moisture-related variability. Organic sulfur, nitrogen, and total sulfur showed positive loadings along PC2, while moisture and ash exhibited negative PC2 contributions. September, November, and December were closely associated with sulfur- and nitrogen-related characteristics, whereas January and February were more associated with increased moisture influence. These results are illustrated in Fig. 2, which presents the principal component analysis (PCA) of the coal parameters.

The seasonal distribution of samples in the PCA biplot revealed clear variability in coal properties throughout the year. April, May, and June were associated with higher calorific value and HHV, indicating better fuel quality and energy performance. In contrast, January and February showed a stronger association with moisture and ash content, suggesting reduced calorific efficiency.

September, November, and December were closely related to organic sulfur, total sulfur, and nitrogen, indicating increased sulfur-related characteristics during these months. March, August, and October were positioned closer to the center of the plot, reflecting

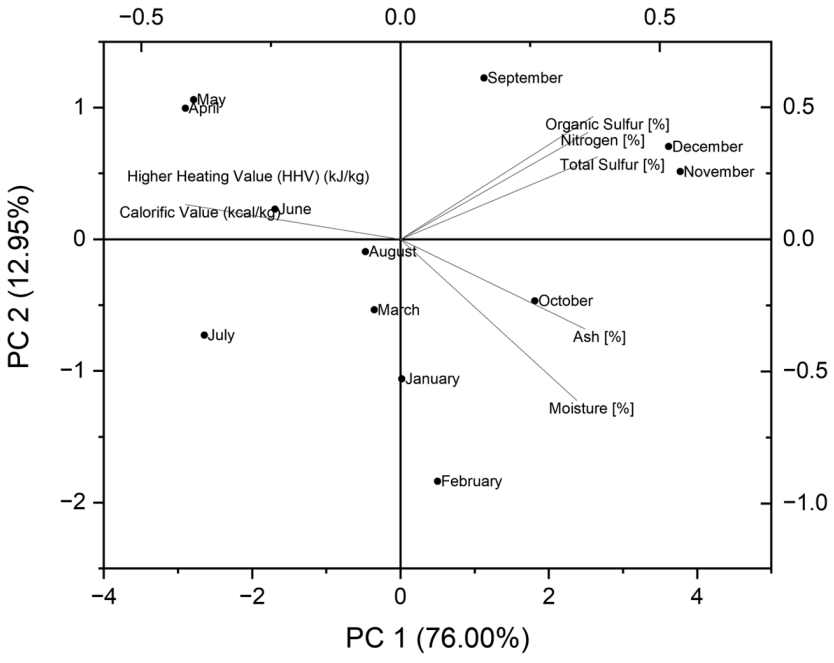


Fig. 2. Principal component analysis (PCA) plot of coal parameters.

more intermediate compositional behavior without the dominance of a specific parameter.

Overall, the PCA demonstrated that spring and early summer months were associated with improved calorific properties, whereas autumn and winter periods showed a stronger influence of sulfur-, ash-, and moisture-related parameters. The eigenvalues, explained variance, cumulative variance, and factor loadings obtained from PCA are presented in Tables 2 and 3 to support the interpretation of the principal components and the relationships among the analyzed variables.

The correlations among variables further supported the PCA interpretation. The nearly perfect relationship between calorific value and HHV ($r \approx 1.00$) confirms that both parameters consistently represent the energy quality of the fuel. The negative correlation between moisture and the energy-related parameters ($r \approx -0.82$) indicates that increasing water content is associated with lower thermal performance of coal. Meanwhile, the positive correlation between total sulfur and organic sulfur ($r \approx 0.91$), as well as between organic sulfur and nitrogen ($r \approx 0.82$), suggests an interconnected behavior of these constituents within the coal matrix and their potential importance in the generation of atmospheric pollutants.

Table 2. Eigenvalues and explained variance of principal components.

Principal Component	Eigenvalue	Explained Variance (%)	Cumulative Variance (%)
Moisture (%)	5.321	76.00%	76.00%
Ash (%)	0.906	12.95%	88.95%
Total Sulfur (%)	0.516	7.38%	96.34%
Organic Sulfur (%)	0.124	1.78%	98.12%
Calorific Value	0.094	1.35%	99.47%
Higher Heating Value (HHV) (kJ/kg)	0.037	0.53%	100.00%
Nitrogen (%)	0	0.00%	100.00%

Table 3. PCA factor loadings of the analyzed variables.

Variable	PC1 Loading	PC2 Loading
Moisture (%)	0.341	-0.610
Ash (%)	0.356	-0.339
Total Sulfur (%)	0.380	0.312
Organic Sulfur (%)	0.371	0.464
Calorific Value	-0.414	0.131
Higher Heating Value (HHV) (kJ/kg)	-0.414	0.131
Nitrogen (%)	0.361	0.404

From an engineering and environmental perspective, these results are consistent with recent studies showing that combustion behavior and NO_x formation in coal-fired systems depend strongly on fuel quality, load regime, ignition stability, devolatilization dynamics, and local temperature fields. In particular, recent research under low-load and variable-load operation has shown that poorer fuel quality can aggravate ignition delay, destabilize combustion, and worsen NO_x behavior, especially when combustion conditions are already constrained by flexible unit operation [27-30]. Experimental and numerical studies also indicate that moisture, nitrogen distribution in the fuel, and coal blending strategy can shift the relative contributions of fuel-NO_x and thermal NO_x, thereby directly affecting emission intensity [31, 32]. Accordingly, the present PCA pattern is not merely a statistical description of seasonality, but also a process-relevant indication that months characterized by wetter, ash-richer, and chemically less favorable fuel are more likely to generate combustion conditions associated with higher NO_x emissions [27, 31].

Overall, the PCA demonstrates that the seasonal variability of coal is governed by a dominant energy-related axis and a secondary axis associated with moisture and organic components, thereby providing an important basis for interpreting the relationship between coal quality and NO_x emissions.

NO_x Emissions Trends

The combined NO_x concentrations from the Kosovo A and Kosovo B thermal power plants ranged from 1161 mg/m³ in June to 2198 mg/m³ in January, exceeding the emission limit values established under Directive 2010/75/EU for large combustion plants. The calculated emission rates (ENOx) varied from 757.61 kg/h to 1408.69 kg/h (presented in Table 4), confirming that coal-fired power generation represents a considerable source of atmospheric nitrogen oxide emissions throughout 2025.

The annual mean NO_x concentrations were 625.36 mg/m³ for Kosovo A, 1043.36 mg/m³ for Kosovo B, and 1668.73 mg/m³ for the combined A+B system (Fig. 3). These results indicate that NO_x levels in stack gases remained consistently elevated during the entire monitoring period.

A comparison between the two power plants shows that Kosovo B systematically maintained higher NO_x concentrations than Kosovo A, thus exerting the dominant influence on the combined A+B values. The higher NO_x concentrations observed in Kosovo B may be associated with its larger production capacity and substantially higher electricity generation compared with Kosovo A, as presented in Table 1. Since Kosovo B operated under higher load conditions during several monitoring periods, the combustion process likely occurred under more intensive operational conditions, which may have favored increased NO_x formation.

Table 4. Monthly NO_x concentrations (mg/m³ and ppm) and calculated ENO_x emission rates (kg/h) from coal combustion in the Kosovo A and Kosovo B thermal power plants during 2025, including comparison with the emission limit values established under Directive 2010/75/EU for large combustion plants [35].

Year 2025	Kosovo A NO_x [mg/m³]	Kosovo B NO_x [mg/m³]	Kosovo A + B NO_x [mg/m³]	Kosovo A NO_x [ppm]	Kosovo B NO_x [ppm]	Kosovo A + B NO_x [ppm]	Industrial Emissions Directive (IED) 2010/75/EU [mg/m³]	ENO_x [kg/h]
January	717.0	1481.0	2198	381.1011	787.1837	1168.3	200-400	1326.01
February	672.0	1251.0	1923	357.1826	664.9337	1022.1	200-400	1408.69
March	679.0	1422.0	2101	360.9033	755.8239	1116.7	200-400	1405.66
April	584.0	844.0	1428	310.4087	448.6043	759.01	200-400	1071.99
May	530.0	745.0	1275	281.7065	395.9837	677.7	200-400	757.61
June	470.0	691.0	1161	249.8152	367.2815	617.1	200-400	779.39
July	683.0	706.0	1389	363.0293	375.2543	738.3	200-400	948.21
August	620.0	789.0	1409	329.5435	419.3707	748.9	200-400	974.64
September	719.0	819.0	1538	382.1641	435.3163	817.5	200-400	1130.15
October	632.0	1361.0	1993	335.9217	723.4011	1059.3	200-400	1229.45
November	573.0	1368.0	1941	304.562	727.1217	1031.7	200-400	1342.64
December	656.0	1295.0	1951	348.6783	688.3207	1036.9	200-400	1340.71

At the same time, ENO_x closely followed the monthly variation in NO_x concentrations, indicating a direct relationship between measured stack-gas concentration and the mass of pollutant emitted per unit time. Seasonal behavior was also evident, with higher values recorded during the winter period, particularly from December to February, and lower values during the summer months, especially from June to August. The monthly electricity generation data also indicated noticeable operational variability throughout the monitoring period. Higher electricity generation during specific months may have contributed to changes in combustion conditions and NO_x formation intensity, suggesting that operational load, together with coal quality characteristics, likely influenced the observed emission patterns.

This pattern suggests the combined influence of operational load, coal quality, and atmospheric conditions on NO_x formation and emission intensity. This interpretation is supported by recent process-oriented studies showing that NO_x generation in utility boilers is controlled by the interaction of multiple operating variables, including excess oxygen,

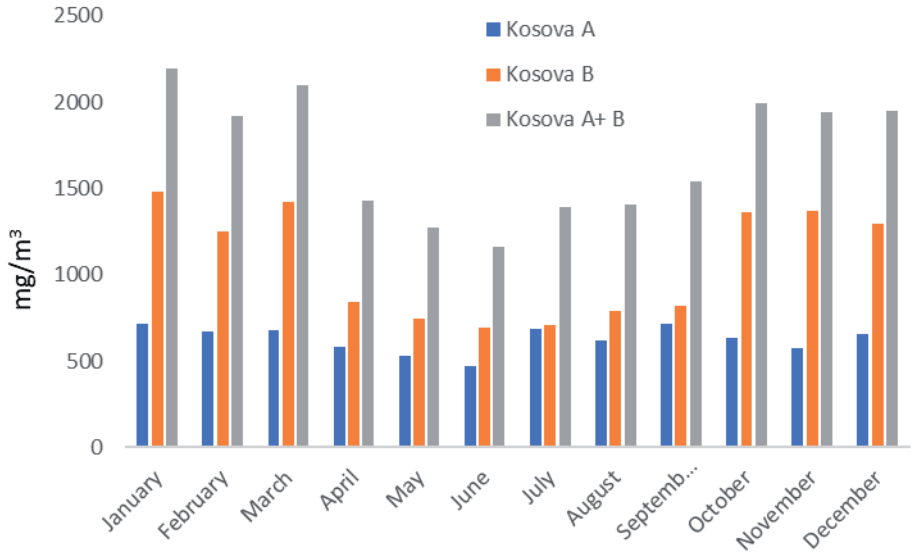


Fig. 3. Trend of NO_x concentrations for the Kosova A and B power plants during 2025.

burner configuration, load level, furnace temperature distribution, airflow organization, and transient operating states [28-30, 33]. Recent machine-learning and deep-learning studies using real plant data have likewise demonstrated that temporal variability in NO_x concentrations reflects nonlinear interactions between process variables and combustion conditions, rather than the isolated effect of a single physicochemical coal property [33, 34]. Therefore, the seasonal peaks observed in the present study are most plausibly interpreted as the combined outcome of less favorable fuel quality and more emission-intensive operating conditions during particular periods of the year [28, 33].

The comparison with the emission limit values established under Directive 2010/75/EU should be interpreted in the context of large combustion plants. Although these limits are intended for industrial emission control rather than ambient air assessment, the consistently elevated NO_x concentrations observed in both thermal power plants indicate a substantial atmospheric pollution potential. The recorded emissions may significantly contribute to the formation of NO_2, tropospheric ozone, and secondary aerosols, with possible implications for air quality, public health, and ecosystem stability. This interpretation is consistent with recent European assessments indicating that large combustion plants remain important contributors to NO_x emissions despite long-term reductions across the EU [15, 16].

Overall, the results indicate that: (i) Kosovo B is the dominant contributor to the total NO_x burden of the combined A+B system; (ii) NO_x concentrations and emission rates remained high throughout the year; (iii) seasonal variability suggests the influence of both operational conditions and coal quality; and (iv) comparison with the emission limits under Directive 2010/75/EU confirms the environmental significance of the recorded emissions.

Multivariate Interactions between Coal Quality Parameters and NO_x Emission Indicators

The Pearson correlation matrix clearly shows (Table 5) that coal quality parameters are significantly associated with both NO_x concentration levels and emission rates expressed as ENO_x. In particular, moisture exhibited a strong positive correlation with both Kosova A+B (r = 0.743, $p<0.01$) and ENO_x (r = 0.777, $p<0.01$), suggesting that an increase in coal moisture content is accompanied by higher emissions. A similar trend was also observed for ash, which showed a relatively high positive correlation with Kosova A+B (r = 0.749, $p < 0.01$) and ENO_x (r = 0.710, $p<0.01$). These findings indicate that coal with higher moisture and ash contents tends to be associated with less efficient combustion performance and, consequently, with increased nitrogen oxide emissions.

This interpretation is supported by recent studies showing that low-grade coal and difficult combustion conditions can increase instability in the furnace and worsen the balance between combustion efficiency and NO_x control [28, 30, 31]. From a combustion-process perspective, the positive association of moisture and ash with NO_x emissions may not necessarily indicate a direct increase in thermal NO_x formation through higher flame temperatures. Instead, increased moisture and ash can modify flame stability, ignition behavior, and local combustion stoichiometry within the furnace. Higher moisture content reduces the effective combustion temperature and delays devolatilization, while elevated ash content dilutes the combustible fraction and may alter local airflow distribution and heat transfer conditions. These effects can contribute to spatial shifts in the combustion zone and to locally oxygen-rich regions that favor NO_x formation, particularly under unstable or variable-load operating conditions. Therefore, the observed correlations likely reflect

Table 5. Pearson correlation matrix of coal quality parameters and NO_x/ENO_x emissions.

Parameter	Moisture [%]	Ash [%]	Total sulfur [%]	Organic sulfur [%]	Calorific value (kcal/kg)	Higher heating value (HHV)	Nitrogen [%]	Kosova A+B	ENO_x
Moisture [%]	1.000	0.778	0.491	0.436	-0.821	-0.821	0.448	0.743	0.777
Ash [%]	0.778	1.000	0.740	0.597	-0.724	-0.724	0.466	0.749	0.710
Total sulfur [%]	0.491	0.740	1.000	0.912	-0.737	-0.737	0.721	0.360	0.369
Organic sulfur [%]	0.436	0.597	0.912	1.000	-0.723	-0.722	0.817	0.297	0.389
Calorific value (kcal/kg)	-0.821	-0.724	-0.737	-0.723	1.000	1.000	-0.803	-0.698	-0.731
Higher heating value (HHV)	-0.821	-0.724	-0.737	-0.722	1.000	1.000	-0.803	-0.698	-0.731
Nitrogen [%]	0.448	0.466	0.721	0.817	-0.803	-0.803	1.000	0.470	0.519
Kosova A+B	0.743	0.749	0.360	0.297	-0.698	-0.698	0.470	1.000	0.933
ENO_x	0.777	0.710	0.369	0.389	-0.731	-0.731	0.519	0.933	1.000

a complex interaction between fuel quality, combustion dynamics, and localized reaction environments rather than the isolated effect of a single coal parameter.

In practical terms, higher moisture reduces the useful heat available for ignition and flame stabilization, whereas higher ash dilutes the combustible fraction and may alter heat transfer, burnout, and local stoichiometric conditions. When these effects occur together, the combustion system becomes more difficult to optimize for low-emission performance, especially under partial-load operation [27, 28].

In contrast, calorific value and higher heating value (HHV) showed strong negative correlations with the emission indicators. Specifically, calorific value was negatively correlated with Kosova A+B (r = –0.698, $p<0.05$) and ENO_x (r = –0.731, $p<0.01$), while HHV exhibited nearly the same pattern, with correlation coefficients of r = –0.698 ($p<0.05$) and r = –0.731 ($p<0.01$), respectively. This implies that coal with higher energy content and better combustion quality tends to produce lower NO_x emissions, supporting the view that improved combustion efficiency contributes to reduced atmospheric pollution. Recent full-scale and predictive studies similarly indicate that NO_x formation becomes increasingly sensitive to the operating window when fuel quality deteriorates, reinforcing the importance of maintaining a favorable thermal profile and stable combustion regime [28, 33, 34]. Regarding the chemical composition of coal, nitrogen showed a moderate positive correlation with Kosova A+B (r = 0.470, $p>0.05$) and ENO_x (r = 0.519, $p>0.05$). This result is consistent with the mechanism of fuel-NO_x formation, in which a higher nitrogen content in the fuel contributes directly to the generation of nitrogen oxides during combustion. Meanwhile, total sulfur and organic sulfur exhibited weak to moderate correlations with the emission indicators, suggesting that their influence on NO_x formation is less direct than that of moisture, ash, nitrogen, and the energy-related parameters. Recent combustion studies likewise confirm that fuel-bound nitrogen remains a critical determinant of original NO_x generation and should be interpreted together with devolatilization behavior and local flame conditions [31, 32].

The matrix also reveals strong interrelationships among the coal quality parameters themselves. Moisture and ash were positively correlated (r = 0.778, $p < 0.01$), while both parameters showed strong negative correlations with calorific value and HHV. This indicates that the deterioration of the physicochemical quality of coal, through increased moisture and non-combustible material content, is directly associated with a reduction in its energy potential. At the same time, total sulfur and organic sulfur showed a very strong positive correlation (r = 0.912, $p<0.001$), demonstrating that these two indicators vary in parallel across the studied samples.

One of the most important findings of this analysis is the very strong positive correlation between Kosova A+B and ENO_x (r = 0.933, $p<0.001$), confirming that an increase in measured NO_x concentration is directly reflected in an increase in the emission rate. This strong relationship supports the internal consistency of the dataset and indicates that both indicators are suitable for assessing the environmental impact of lignite-fired power plants. Overall, the Pearson correlation results suggest that moisture, ash, and, to a lesser extent, nitrogen are positively associated with increased NO_x emissions, whereas calorific value and HHV contribute to their reduction. These findings support the conclusion that improving coal quality and optimizing its energy-related characteristics may represent an important strategy for reducing nitrogen oxide emissions in lignite-based thermal power plants.

Distribution of NOx Emissions across the Analyzed Power Plant Series

The NO_x box plots presented in Fig. 4 provide a concise statistical summary of the monthly emission distributions for Kosova A, Kosova B, and the combined A+B series. Kosova A is characterized by the narrowest interquartile range and the shortest whisker span,

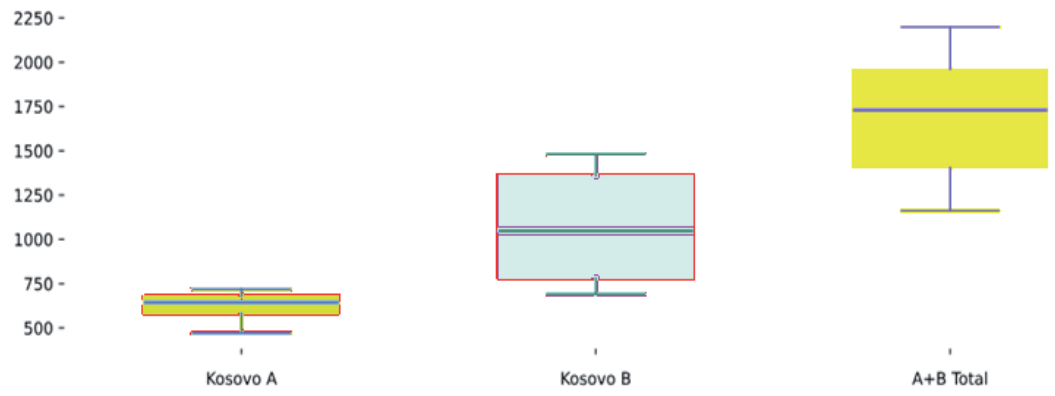


Fig. 4. Box plot distribution of NO_x emissions for Kosova A, Kosova B, and the combined A+B series.

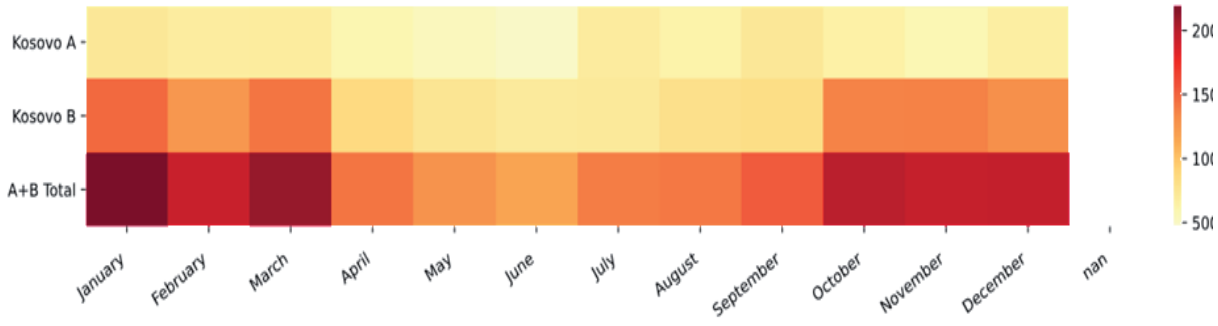


Fig. 5. Seasonal heatmap of NO_x emissions for Kosova A, Kosova B, and the combined A+B sources.

indicating lower dispersion and a more stable monthly emission pattern throughout the year. In contrast, Kosova B exhibits a markedly wider box and broader whisker range, reflecting greater variability and more pronounced month-to-month fluctuations in NO_x emissions. The combined A+B series shows the highest median together with the widest overall distribution, confirming that the cumulative emission profile is influenced by both the higher contribution of Kosova B and the additive effect of simultaneous operation of the two power plants. Furthermore, no pronounced outliers are visible in the figure, suggesting that the observed variability is systematic rather than the result of isolated extreme events. Overall, the box plot analysis demonstrates that total NO_x emissions are controlled not only by the average emission level of each power plant, but also by their temporal variability and combined operational contribution.

The seasonal heatmap presented in Fig. 5 clearly illustrates month-to-month variations in NO_x emission intensity for Kosova A, Kosova B, and the combined A+B series. Kosova A is characterized by lower values and relatively limited variation throughout the year, whereas Kosova B exhibits higher intensity and more pronounced monthly fluctuations. The combined A+B series shows the highest values across nearly the entire period, with particularly elevated intensities at the beginning and the end of the year. This visual pattern suggests the presence of a seasonal distribution of emissions, in which the winter months and late autumn tend to be associated with higher NO_x levels compared with the spring–summer period. Overall, the figure confirms that emissions are not uniform throughout the year, but instead follow a distinct temporal pattern that may be related to plant operating conditions and load demand.

The occurrence of months with higher emission intensity suggests that, under the observed operating regime, emission control performance was not equally effective throughout the year. However, since the present assessment is based on monthly aggregates, it does not capture within-month variability, short-term episodic events, or the influence of specific meteorological and operational factors. For this reason, the results should be interpreted as indicators of temporal patterns rather than as direct evidence of causality. A more comprehensive evaluation of compliance and emission-driving factors would require the integration of operational data, unit maintenance records, and monitoring QA/QC information. This is also consistent with recent studies showing that a more robust interpretation of stack-gas behavior is achieved when concentration data are combined with real-time operational variables and data-driven modeling approaches [33, 34].

Conclusions

This study showed that the physicochemical quality of lignite used in the Kosova A and Kosova B power plants during 2025 exhibited pronounced seasonal variability, reflected in changes in moisture, ash, sulfur, nitrogen, calorific value, and higher heating value (HHV). These variations confirm that fuel properties are not constant throughout the year and directly affect the combustion process and the NO_x emission profile.

Principal component analysis (PCA) demonstrated that the variation in coal parameters could be effectively described by two principal components, which explained about 89% of the total variance. The first component was mainly associated with the energetic dimension of coal, whereas the second reflected the influence of moisture and chemical composition. This indicates that lignite behavior during combustion is determined by the interaction between its energy-related and physicochemical properties.

The emission results showed that NO_x concentrations remained high throughout the year, with a more pronounced contribution from Kosova B and higher intensity in the combined A+B series. Graphical and statistical analyses confirmed that emissions were not temporally uniform, but followed a distinct seasonal and operational pattern.

Pearson correlation analysis confirmed that moisture, ash, and nitrogen were positively associated with increasing emission indicators, whereas calorific value and HHV were negatively associated with NO_x and ENO_x. These relationships indicate that coal with

lower energy quality and a higher content of non-combustible fractions tends to generate higher nitrogen oxide emissions.

Overall, this study demonstrates that NO_x emissions in lignite-fired power plants result from the interaction between fuel quality and combustion operating conditions. The findings highlight the need for continuous coal quality monitoring, integration of laboratory data with operational parameters, and optimization of combustion processes in order to reduce NO_x emissions and improve the environmental performance of thermal power plants.

Conflict of Interest

The authors declare that the present study was conducted in the absence of any conflict of interest.

AI Usage Disclosure Statement

While preparing this manuscript, the authors employed ChatGPT to enhance language, correct grammar, and clarify English expressions. The AI was not involved in generating data, designing experiments, performing statistical analyses, creating figures, interpreting results, or forming scientific conclusions. All AI-assisted content was thoroughly reviewed, edited, validated, and approved by the authors. The authors assume full responsibility for the manuscript's accuracy, integrity, and originality.

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