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THE EFFECT OF POWER PLANT CHARACTERISTICS ON CO_2 EMISSION FACTOR DEVELOPMENT: A CASE STUDY OF COAL-FIRED POWER PLANTS IN INDONESIA

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Abstract

The emission factor (EF) describes the relationship between pollutants released into the atmosphere and associated activities. Developing specific EFs is essential for accurate emission calculations in the industrial sector, particularly in coal-fired power plants (CFPPs), a major source of emissions in Indonesia. This study aims to develop specific CO_2 EFs for CFPPs in Indonesia by analyzing the influence of power plant characteristics, such as technology type and age, on the EF values. The EFs, expressed in tons of CO_2 per unit of energy produced ($t\ TJ^{-1}$), are based on data from 153 units across 66 CFPPs in Indonesia. Five technology types were included in the analysis: ultra-supercritical, super-critical, subcritical-pulverized coal combustion, subcritical-fluidized bed combustion and subcritical–stoker. The study compares the resulting CO_2 EFs with the IPCC-2006 default value for sub-bituminous coal and Indonesia's national EF for medium-quality coal. The average CO_2 EF for Indonesian CFPPs was 100.16 $t\ TJ^{-1}$, higher than the IPCC-2006 default value (96.1 $t\ TJ^{-1}$) but slightly lower than Indonesia's national EF (100.575 $t\ TJ^{-1}$). A statistical test revealed significant differences between technology and age groups, but post-hoc analysis showed no strong correlation was found between these characteristics and the EF values within specific groups. This indicates that the EF, based on fuel characteristics, is not directly influenced by these plant characteristics. It is hoped that the CO_2 EF values obtained from this study will better represent actual conditions, provide a more accurate emission calculations and supporting the development of better emission inventories for cleaner energy generation.

Keywords: *emission factor, CO_2, coal-fired power plant, technology types, age*

Introduction

Concerns related to emission inventories and efforts to reduce emissions have increased globally, including in Indonesia. Emission assessments related to specific industrial sources or activities are becoming increasingly important in air quality management (Efendy & Dewi, 2023). In line with this, Indonesia has committed to and is actively working to reduce Greenhouse Gas (GHG) emissions, particularly in the energy sector, by ratifying the Paris Agreement to the United Nations Framework Convention on Climate Change with Law No. 16 of 2017 on October 24, 2017. Based on the "New Climate Regime" in the Paris Agreement, global inventories will be conducted at 5-year intervals starting in 2023, and national GHG inventories and reductions must be reported (UNFCCC, 2015). To prepare for the global inventory, it is important to improve the emission inventories

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and understand the characteristics of its sources (Kang et al., 2020).

According to Indonesia's Energy Balance data published by the Central Bureau of Statistics, in 2021, Indonesia's energy consumption reached 6.9 million TJ. The coal sector played a significant role, with domestic coal consumption in Indonesia reaching 138.5 million tons that year. Coal Fired Power Plants (CFPPs), which are the largest coal consumers in Indonesia, consumed 129 million tons of coal, accounting for about 60% of the national coal consumption in 2022 (Kementerian Energi dan Sumber Daya Mineral, 2023).

CFPP are one of the main contributors to GHG emissions, particularly carbon dioxide (CO_2) emissions (Nunes, 2023) CO_2, released during the coal combustion process, is a greenhouse gas that significantly contributes to global warming and climate change. The amount of CO_2 emitted by a CFPP, known as the CO_2 Emission Factor (EF), can be influenced by several factors, including the specifications and characteristics of the plant itself, such as the type of technology used, the age of the plant, the emission control equipment, and more. EFs, expressed as the mass of pollutants emitted per unit of activity (fuel consumption or unit of production), are closely related to the characteristics of the source. In the context of power plants, EF data are essential for calculating the amount of CO_2 emissions per unit of energy produced, typically expressed in $t\ TJ^{-1}$. The most accurate EFs are those which are prepared from plant-specific data, obtained from each plant individually (Sloss, 2011). By knowing the EF for CO_2 at a power plant unit, the amount of emissions produced at a certain level can be quickly determined. However, in reality, EF data for each power plant in Indonesia are difficult to obtain, and even when available, they are only average data from a few plants in Indonesia (Budi & Suparman, 2013).

Most of the power plants operating in Indonesia use subcritical technology, a conventional power plant with steam temperature in the vicinity of 820 K and pressure around 16–17 Mpa, which has which has a thermal efficiency of only around 38% (Zhang, 2013). This technology is the least efficient and most polluting form of coal fired generation (Caldecott et al., 2015). It generates more CO_2 per unit of energy produced because more coal needs to be burned to achieve the desired output level. In contrast, supercritical generation technologies are more efficient and much cleaner than subcritical generation units (Mohamed et al., 2020). Newer technologies such as supercritical and ultra-supercritical use much higher pressures and temperatures, allowing for higher combustion efficiency and, in turn, reducing CO_2 emissions per terajoule (TJ) of energy produced.

In addition to technology type, the age of the power plant also plays an important role in determining the CO_2 EF. Because of the aging CFPPs and so their equipment, it also produces less power than their installed capacities, and there has been power loss in time (Cetin & Abacioglu, 2013). Older power plants tend to experience operational efficiency declines due to equipment degradation, such as turbines and boilers. As efficiency decreases, more coal is required to produce the same amount of energy, which automatically increases CO_2 emissions. Furthermore, many older power plants are not equipped with the latest emission reduction technologies, making them less effective in reducing CO_2 output compared to newer plants. CFPPs must make efficiency improvement and should be subjected to tighter emission standard, especially the existing older power plants (Guttikunda & Jawahar, 2014). Power plants that have been operating for decades may not comply with stricter environmental regulations implemented more recently, potentially leading to higher CO_2 emissions.

Given that CFPPs in Indonesia are one of the largest contributors to CO_2 emissions, research is needed on the development of EFs from power plant units, taking into account specific characteristics, namely the type of technology and the age of the power plant. This research is conducted using statistical analysis to address existing gaps by developing specific CO_2 EFs based on the characteristics of CFPP, which will then be compared with the default EF values from the Intergovernmental Panel on Climate Change 2006 (IPCC-2006) and national EFs. Although widely used, the default IPCC-2006 value is a global average used for national inventories, and it may not be suitable for use in certain power plant units (Kementerian Energi dan Sumber Daya Mineral, 2019). Therefore, this study aims to develop specific CO_2 EFs for CFPPs in Indonesia by analyzing the influence of power plant characteristics, such as technology type and age, on the EF values.

Research Methodology

Data Collection and Analysis

Data was collected from periodic reports submitted by power generation companies in Indonesia to the government through the Electricity Emissions Calculation and Reporting Application (APPLE-GATRIK), a web-based tool for calculating and reporting greenhouse gas (GHG) emissions from power generation units to the Directorate General of Electricity, Ministry of Energy and Mineral Resources. Data was taken from 153 units across 66 CFPPs operating in Indonesia. The technologies used by these units include 7 ultra-supercritical units, 7 supercritical units, 65 subcritical-pulverized coal combustion units, 53 subcritical-fluidized bed combustion units, and 21 subcritical-stoker units. Collected data includes type of technology, operational start time (age), electricity generated, coal consumption, coal's NCV value, the carbon content of coal, and unburned carbon content in the coal. The data was then analyzed, and calculations were performed to determine the EF for each unit.

CO_2 EF Calculation Method

The data processing in this study follows a mass balance calculation approach. This method is used to estimate emissions through stoichiometric calculations. For calculating the CO_2 EF, the available data plays an important role in determining the calculation method used. Based on the Guidelines for Calculation and Reporting of Greenhouse Gas Inventory in the Energy Sector - Subsector of Electricity issued by the Ministry of Energy and Mineral Resources, referring to IPCC-2006, the available data can describe different tiers, where the higher the tier, the more accurate the results. The following matrix describes the tiers and their relationship to the calculation methods used.

Table 1. CO_2 Emission Calculation Tier Matrix

Tier	Required Data	Output
Tier-1	Fuel consumption, IPCC-2006 default EF and net calorific value (NCV)	CO_2 emission
Tier-2	Fuel consumption, national default NCV, national EF	CO_2 emission
	Fuel consumption, national/ specific NCV, carbon content of coal, and default oxidation factor	CO_2 emission, Plant-specific EF
Tier-3	Fuel consumption, specific NCV, carbon content of coal, and specific oxidation factor	CO_2 emission, Plant-specific EF
	Fuel consumption, specific NCV, carbon content of coal, ash content and unburned carbon of coal	CO_2 emission, Plant-specific EF

In this study, with the availability of specific NCV data, specific oxidation factors, carbon content data, and unburnt carbon in the coal used, the calculation results can be classified as Tier-2 or Tier-3. According to IPCC-2006, CO_2 EFs are calculated using Eq. (1-4).

$$EF_{CO_2} = \frac{E_{CO_2}}{AD \times OF} \tag{1}$$

EFs in this study will be calculated through analysis using the mass balance method based on fuel characteristic calculations, so the following equation will be used:

$$E_{CO_2} = F_{coal} \times CC_{coal} \times OF \times \frac{44}{12} \tag{2}$$

$$AD = F_{coal} \times NCV \times 10^{-3} \tag{3}$$

therefore,

$$EF_{CO_2} = \frac{CC_{coal}}{NCV} \times \frac{44}{12} \times 10^{3} \tag{4}$$

where EF_{CO_2} is the CO_2 emission factor (t TJ^{-1}), AD is the activity data, OF is the oxidation factor (%), F_{coal} is the coal consumption (t), CC_{coal} is the carbon content of the coal (%), NCV is the net calorific value of the coal (TJ Gg^{-1}), 44 is the molecular weight of CO_2, and 12 is the atomic weight of carbon (C).

Statistical Analysis Method

After obtaining the CO_2 EFs for each power plant unit, statistical analysis is conducted. The first step is to group the data into two specific characteristics, based on the technology type and the age of the power plants. Each data group is visualized using graphical representations such as boxplots. In statistics, a boxplot is a graphical summary of sample distribution, illustrating data distribution (skewness), central tendency, and data variability (spread of observations). Three horizontal lines are drawn for each group, one line each at the lower and upper quartiles and another at the median (Mcbean, 1998).

The results from the boxplot interpretation are then reinforced by conducting a normality test using the Shapiro-Wilk or Kolmogorov-Smirnov test. According to Razali & Wah (2011), the Shapiro-Wilk test is the most powerful test for all types of distribution and sample sizes, when compared with Kolmogorov-Smirnov test. If the normality test shows that the data is normally distributed, an ANOVA (Analysis of Variance) test is performed to examine if there are significant differences between the average EFs across different technologies or plant ages. If the data is not normally distributed, the Kruskal-Wallis test, a non-parametric version of ANOVA that does not require normality assumptions, can be used. In particular, this test is often used when (and because) a parametric ANOVA is not appropriate (Ruxton & Beauchamp, 2008). This test compares the median EFs between various data groups.

If the tests indicate significant differences between variables, a post-hoc test can be performed to identify which variables significantly differ. The post-hoc tests that can be used include Tukey's HSD test (for data that meets normality assumptions) and Dunn's test (for data that does not meet normality assumptions). Figure 1 illustrates the flow of how the statistical analysis is conducted.

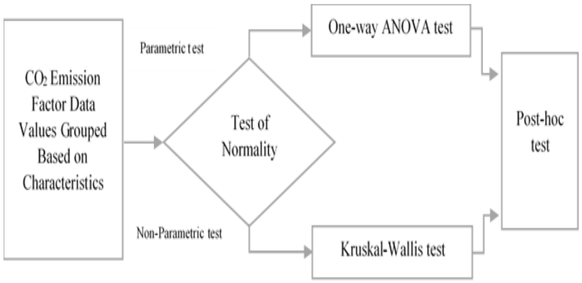

Figure 1. Statistical Analysis Flow

In this study, the statistical analysis will be performed using R software to simplify the calculations. To determine whether specific characteristics of a power generation unit affect the CO_2 EF value, comparisons of the average EF distribution based on technology type and unit age will be conducted.

Results and Discussion

CO_2 EF Values in Previous Studies

The EF values retrieved from the mass balance approach in this study, will be compared to widely-used EFs, such as those given by the

IPCC-2006, National EFs (country specific) and other studies, which is shown in table 2.

Table 2. CO_2 EF Values from Various Sources

Source	EF (t TJ^{-1})	Reference
IPCC-2006 Guidelines	96.1[a]	Eggleston et al., 2006
Applied Energy (Elsevier)	97.9	Jeon et al., 2009
R&D Center for Mineral & Coal	100.575[b]	Damayanti et al., 2018
ITS (Thesis)	107.17	Erfian et al., 2024

[a] for sub-bituminous coal

[b] for medium rank coal

Furthermore, the emission factor values in table 2, particularly widely-used EFs, will be used as a reference or basis for comparison with the emission factor values developed from this research. The CO_2 EFs that have been calculated using the equation previously explained are then characterized based on the type of technology and the age of the CFPP.

EFs Based on Technology Types

The EFs are developed for each type of CFPPs technology to understand the characteristics that affect CO_2 emissions.

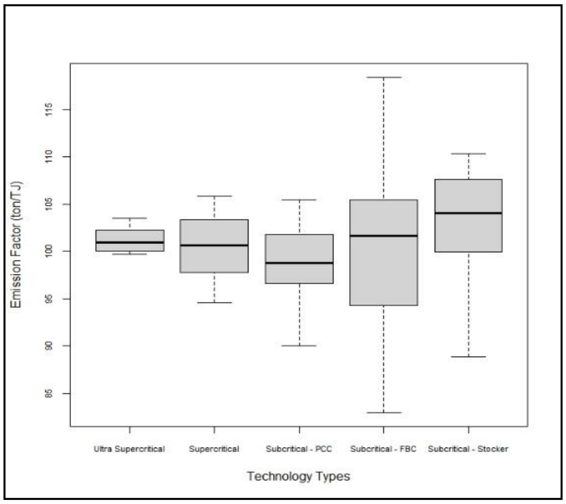

Figure 2. Boxplot of CO_2 EFs Based on Technology Type

The distribution of CO_2 EF values, developed based on the different technologies, is displayed through statistical analysis as shown in Figure 2. Based on the boxplot in Figure 2, several key insights can be gathered regarding the EFs for each CFPP technology. The ultra supercritical units were analyzed with the maximum CO_2 EF is 103.48 t TJ^{-1}, the minimum is 99.7 t TJ^{-1}, and the median is 100.97 t TJ^{-1}. Supercritical units were analyzed with the maximum value is 105.82 t TJ^{-1}, the minimum is 94.56 t TJ^{-1}, with a median of 100.66 t TJ^{-1}. Subcritical-pulverized coal combustion units were analyzed with the maximum is 105.41 t TJ^{-1}, the minimum is 90.02 t TJ^{-1}, and the median is 98.8 t TJ^{-1}. Subcritical-fluidized bed coal units were analyzed with a maximum EF of 118.41 t TJ^{-1}, a minimum of 82.96 t TJ^{-1}, and a median of 101.68 t TJ^{-1}. The EFs range from a maximum of 110.35 t TJ^{-1} to a minimum of 88.89 t TJ^{-1}, with a median of 104.06 t TJ^{-1} for subcritical (stoker) units.

From the boxplot, it is evident that the ultra supercritical and supercritical units display more symmetrical distributions with shorter whiskers, suggesting more consistent emission values. In contrast, subcritical-fluidized bed coal and subcritical-stoker show more skewed distributions with longer whiskers, particularly for subcritical-fluidized bed coal, indicating greater variability at both ends of the distribution. To verify whether the data is normally distributed, a Shapiro-Wilk test was conducted. The p-value of 0.001049 (<0.05) suggests that the data is not normally distributed, confirming that further non-parametric analysis may be required for these data sets.

Table 3. CO_2 EF Based on Technology Type

Technology Types	Units	Developed EF (t CO_2 TJ^{-1})
Ultra Supercritical	7	101.24
Supercritical	7	100.47
Subcritical - PCC	65	99.18
Subcritical - FBC	53	100.23
Subcritical - Stoker	21	102.7
Total	153	Avg. : 100.16

Table 3 presents the average CO_2 EFs for each type of technology. When calculating the overall average EF for all technology types, it is found that the CO_2 EF for CFPPs in Indonesia is 100.16 t TJ^{-1}. This value is higher than the IPCC-2006 default EF for sub-bituminous coal, which is 96.1 t TJ^{-1}, and slightly below the national EF for medium-quality coal, which is 100.575 t TJ^{-1}.

EFs Based on Plant Unit Age

In this section, EFs were developed by grouping power plant units of CFPPs using subcritical-fluidized bed combustion technology based on their age (year of operation commencement). This was done to understand the characteristics and assess the impact of the unit's age on CO_2 emissions. This particular technology type was chosen because it exhibits high variability in emissions, as indicated by a wide interquartile range and long whiskers on the boxplot, suggesting that multiple factors, including plant age, may influence emissions. The distribution of CO_2 EF values based on the age of the power plants is displayed through a statistical analysis shown in Figure 3. This analysis aims to assess whether older power plants tend to have higher CO_2 EFs due to reduced efficiency or technological degradation over time.

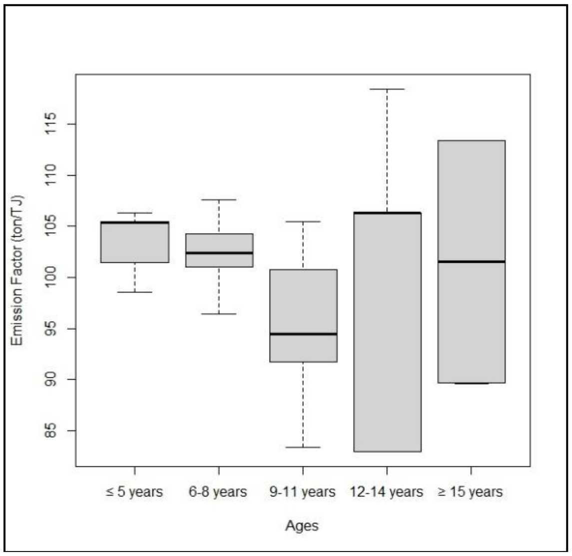

Figure 3. Boxplot of CO_2 EFs Based on Age

Based on the box plot in Figure 3, several insights can be drawn regarding the EFs of each CFPPs based on the grouping by age. Units aged < 5 years were analyzed with the maximum CO_2 EF is 106.31 t TJ^{-1}, the minimum is 98.54 t TJ^{-1}, and the median is 105.4 t TJ^{-1}. Units aged 6-8 years were analyzed with a maximum value is 107.54 t TJ^{-1}, the minimum is 96.44 t TJ^{-1}, and the median is 102.34 t TJ^{-1}. Units aged 9-11 years were analyzed with the maximum is 105.48 t TJ^{-1}, the minimum is 83.35 t TJ^{-1}, and the median is 94.44 t TJ^{-1}. Units aged 12-14 years were analyzed with the maximum is 118.41 t TJ^{-1}, the minimum is 82.96 t TJ^{-1}, and the median is 106.31 t TJ^{-1}. Units aged ≥ 15 years were analyzed with the maximum EF is 113.39 t TJ^{-1}, the minimum is 89.6 t TJ^{-1}, and the median is 101.56 t TJ^{-1}.

From the boxplot in Figure 3, there are also indications that the data distribution might not be normal. Power plants in the ≤ 5 years and 6-8 years groups appear to have relatively symmetrical distributions with small variations, suggesting normal distribution. The 9-11 years group shows slight skewness, but the distribution remains fairly balanced. The 12-14 years and ≥ 15 years groups indicate strong signs of non-normality, with positive skewness and large variations. To confirm the normality of the data, a Shapiro-Wilk test was conducted. The test yielded a p-value of 0.01505 (<0.05), which indicates that the data does not follow a normal distribution.

Table 4. EF Values Based on Ages

Ages	**Units**	**Developed EF (tCO_2 TJ^{-1})**
≤5 years	11	103.81
6-8 years	17	102.41
9-11 years	16	95.35
12-14 years	5	99.39
≥15 years	4	101.53
Total	53	Mean : 100.498

In Table 4, the average CO_2 EF values for each age group of power generation units are shown. It is noted that the highest EF, which is 103.81 t TJ^{-1}, was obtained from the power generation units in the age group of ≤ 5 years, while the lowest EF is shown by the units in the 9-11 year age group, at 95.35 t TJ^{-1}. When calculating the overall average EF for all age groups, it is known that the CO_2 EF from CFPPs using subcritical-fluidized bed combustion technology is 100.498 t TJ^{-1}. This is higher than the default EF value from the IPCC-2006 for sub-bituminous coal, which is 96.1 t TJ^{-1}, and slightly below the national EF value for medium-quality coal, which is 100.575 t TJ^{-1}.

The Effect of Technology Type and Age on EFs

The next step is to conduct a statistical test to determine whether there is a relationship between the technology type and age variables on the EF. The statistical test is conducted using the Kruskal-Wallis test. Kruskal-Wallis is a non-parametric test used to compare three or more independent groups on a single measurable variable. This test is an alternative to one-way ANOVA when the assumption of normality is not met. The non-parametric Kruskal-Wallis test is chosen to compare average distributions to determine whether the CO_2 EF is influenced by the type of technology and the age of the power plant units. The results of this test are shown in Tables 5 and 6.

Table 5. Kruskal-Wallis Test Results on CO_2 EF for Technology Type

Hypothesis Test	Null Hypothesis	Test Results & Decision
CO_2 EF for power plant technology type	No significant difference, all groups come from the same population.	P-value = 0.03539 (< 0.05) Reject the null hypothesis. There is a significant difference between technology types.

From the Kruskal-Wallis test results for the technology-type groups of power plants, a p-value of 0.03539 is obtained, which is smaller than the determined significance level (α) of 0.05. Therefore, it can be concluded that there is a significant difference between the technology-type groups. This indicates that there is likely a relationship between the EF and the technology type of the power plant units.

To determine which variables, differ significantly in terms of CO_2 EFs, a post-hoc test was conducted. The test used is Dunn's Test, which is a common post-hoc test used after performing the Kruskal-Wallis test. Dunn's Test makes pairwise comparisons between groups, correcting for type I errors (false positives) that may arise due to the large number of pairwise comparisons. To ensure the validity of the post-hoc results given the number of pairwise comparisons, a correction is also applied. The correction used is the Bonferroni Correction, which divides the α value (0.05) by the number of comparisons made. After conducting the test, it was found that none of the groups showed a significant difference in EFs. This suggests that the type of technology used in the power plant units, within the analyzed categories, does not have a significant impact on the EF.

Table 6. Kruskal-Wallis Test Results on CO_2 EF for the Age Power Plant Units

Hypothesis Test	Null Hypothesis	Test Results & Decision
CO_2 EF for the ages of power plant units	No significant difference, all groups come from the same population.	P-value = 0.04565 (< 0.05) Reject the null hypothesis. There is a significant difference between age groups.

Meanwhile, from the results of the Kruskal-Wallis test for the age group of power plant units, a p-value of 0.04565 was obtained, which is smaller than the significance level (α) set at 0.05. Therefore, it can be concluded that there is a significant difference between the age groups. This indicates that there is likely a relationship between the EF and the age of power plant units.

After conducting a post-hoc test using Dunn's Test, it was found that no age group showed a significant difference in EFs. Although there was a p-value of 0.0419 approaching the significance level between the 9-11 year group and the ≤ 5 year group, this result was not significant after applying the Bonferroni correction. This suggests that the age of the power plant units within the analyzed categories does not significantly affect the EF.

Conclusions

This study attempts to develop EFs based on fuel characteristics, expressed in units of tons of CO_2 per energy produced ($t\ TJ^{-1}$) and analyzes the effect of CFPP unit characteristics, including technology types and age on CO_2 EFs. Samples were obtained from 153 units in 66 CFPPs operating in Indonesia.

Based on the results, the average CO_2 EF obtained was 100.16 $t\ TJ^{-1}$, which is higher than the default IPCC-2006 EF (96.1 $t\ TJ^{-1}$) and slightly below the national EF (100.575 $t\ TJ^{-1}$). For all age groups, the average CO_2 EF for power plants using subcritical-fluidized bed combustion technology is 100.498 $t\ TJ^{-1}$, which is higher than the IPCC-2006 EF but slightly below the national EF. Based on statistical analysis, there was no significant difference in EF values between the technology or age groups, indicating that within the analyzed categories, neither technology type nor age of the power plant significantly affects the EF. The occurrence mentioned in the test should be acknowledged and it is important to note that the EFs calculation method utilizes fuel characteristics, which are expressed in units of tons of CO_2 per energy produced, is not directly linked to the technology or age of the power generation unit.

In conclusion, the EF values based on fuel characteristics obtained from this study are expected to accurately represent real-world conditions of power plant units and lead to more precise emission calculations. It is recommended to obtain more detailed data on the coal quality used by each plant to further improve EF accuracy. Additionally, this study focused solely on CFPPs, so future research should also involve comparisons with power plants using fuels other than coal.

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