Enhancing soil quality with coal fly ash amendment: a waste recycling approach for climate change mitigation in Indonesia - a review

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Abstract. Coal fly ash (CFA), a byproduct of coal combustion (CCP) from electric/thermal power plants, was classified as hazardous and toxic waste under Government Regulation Number 104/2014 in Indonesia. However, a significant shift in this regulatory viewpoint developed with the introduction of Government Regulation Number 22/2021. This regulation fundamentally altered the treatment and classification of CFA. Managing CFA as a waste has been both extensive and costly. In various countries where CFA is classified as non-hazardous and non-toxic waste, its utilization spans various sectors. Agriculture is a notable sector benefiting from CFA, as it is applied to soil amendment. As a soil amendment, CFA enhances nutrient availability and soil fertility, promotes plant development, and positively alters soil physical properties. In addition, CFA application to soil improves soil carbon storage, contributing to climate change mitigation and adaptation. This paper aims to review Indonesia's state of CFA utilization before the enactment of Government Regulation Number 22/2021, in order to present insights into the potential for expanded CFA utilization in soil amendment following the new regulation (Government Regulation Number 22/2021).

1 Introduction

Fly ash bottom ash (FABA) is categorized as hazardous-toxic waste under Government Regulation No. 85/1999 on Hazardous-Toxic Waste Management. This regulation mandates a comprehensive life-cycle approach for managing hazardous-toxic waste, from generation to final disposal, with strict handling protocols. Specialized permits are required at each phase of FABA waste management, including storage, collection, transportation, treatment, utilization, and landfill operations [1]. However, classifying FABA as hazardous-toxic waste contradicts Indonesia's Coal Development and Utilization roadmap [2]. In contrast, some countries label FABA as non-hazardous, non-toxic waste, enabling its full-scale utilization. Notably, Indonesia's major coal export destinations—China, India, and South Korea—do not

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categorize FABA as hazardous-toxic waste. China and India classify it as solid waste, while South Korea defines FABA as a specific byproduct [3,4].

In 2021, the Government of Indonesia officially delisted FABA from the hazardous-toxic waste category, in accordance with Government Regulation No. 22/2021 on the Implementation of Environmental Protection and Management. This policy revision was rendered on the basis that FABA satisfies the criteria for classification as nonhazardous-nontoxic waste. FABA exhibits neither flammable nor explosive characteristics, demonstrates a lack of reactivity, and is non-corrosive in nature. Empirical assessments, including the Toxicity Characteristic Leaching Procedure (TCLP), evaluations of heavy metal content, and Lethal Dose 50 (LD 50) tests, further confirm that FABA complies quality standards for non-hazardous, non-toxic waste [5]. Despite its classification as nonhazardous-nontoxic waste, producers of such waste are still comply with the established standards and technical criteria as stipulated in the approved environmental documentation, issued by the government (central or local). The removal of FABA from the hazardous-toxic waste classification is expected to increase FABA utilization.

Nevertheless, this manuscript will primarily focus on exploring the potential application of coal fly ash (CFA) as a soil amendment to enhance soil quality, particularly after the revocation of its hazardous-toxic waste status after the Government Regulation application. The implementation of the regulation will expand opportunities for CFA reuse/recycling, not only in the construction sector. Additionally, the paper will elucidate CFA's role in climate change mitigation strategies and enhancing carbon stock in soil. This projection is consistent with Yao et al. [6] that reuse/recycle CFA as an alternative to landfill disposal has the potential to yield substantial economic and environmental advantages.

2 Elemental properties of CFA and its effect on soil chemical properties

Numerous scientific investigations have confirmed the effectiveness of CFA as a promising soil amendment, enhancing soil nutrient availability, thereby ameliorating soil fertility and promoting plant development [7]. Significant amounts of Si, Al, Fe, Ca, K, S, Na, and Mo, along with trace elements, are present in CFA. Moreover, Yu et al. [8] reported that CFA incorporates both macro and micro nutrients including P, Mg, B, Co, Cu, Mn, Ni, and Zn which are essential for plant growth and development. CFA with elevated Ca concentration serves as an effective liming agent [9], an important role as soil amendment. However, contrasting observations were presented by Jackson et al. [10], who indicated that the macro-nutrient concentration in CFA is lower, requiring its combination with additional organic materials like manure or sewage sludge for soil amendment applications. While the P content in CFA is modestly elevated relative to its concentration in native soil, it predominantly exists in a phase that is not readily bioavailable. This is because it is largely bound to aluminosilicate minerals, making it less soluble and therefore less available to plants [11–13]. Conversely, Ca, Mg, K, and Na concentrations are significant and bioavailable [11,14,15].

The American Society for Testing Materials (ASTM) classifies CFA into two classes: Class F contains more than 70% combined silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), while Class C comprises these elements in a range of 50 to 70% [16]. Class C CFA are distinguished by their higher CaO content when compared to Class F CFA. Generally, Class C CFA contains > 15% CaO, while Class F CFA typically contains < 15% CaO [6]. Class C CFA with higher calcium content is generated through lignite or sub-bituminous (soft coal) combustion, while class F CFA is produced through combustion of anthracite and bituminous (hard coal). Class F CFA exhibits pozzolanic characteristics, indicating that it contains Si compounds that will react with $Ca(OH)_2$ at ambient temperatures to create a new compounds with cementitious properties. On the contrary, class C CFA (higher content of

CaO) exhibits inherent self-cementing property. When it reacts with water, class C CFA will harden and increase its strength over time [16].

CFA effectively raises soil pH, largely due to its inherent alkalinity. In addition, replacing lime with CFA has the potential to reduce CO_2 emissions generated during lime production, thereby serving as dual approach for climate change adaptation and mitigation. Class C CFA has been empirically demonstrated to elevate soil pH and mitigate soil acidity [17]. Manoharan et al. [18] reported an elevation of approximately two pH units in topsoil (0-10 cm depth) with an application dose of 108 t ha^{-1} of CFA. The gradual increase of soil pH after CFA application could be mediated by the consumption of H^+ during the weathering of alumino-silicate minerals and the dissolution of calcium from CFA [19,20]. Elevations in soil pH also influence the solubility and bioavailability of soil nutrients [18,21]. Comprehensive compositional analysis of Indonesian-sourced CFA has been conducted to catalog its constituent elements, and CFA that was used for soil amendment in Indonesia and other countries (Table 1). In Table 1, the soil amendments under consideration exhibit high/alkaline pH levels, despite presenting a relatively low concentration of Ca.

Table 1. Elemental CFA content as for identification and as for soil amendment.

Constituents and Characteristics	Unit	CFA [a]		CFA [b]	CFA [c]	CFA [d]
		East Java	West Java	North Halmahera	Bangka	South Africa
SiO_2	%	41.3	51.3	nm	85.86	55.1
Al_2O_3	%	29.5	34.6	nm	5.40	28.6
Fe_2O_3	%	11.55	5.11	2.96	10.30	5.60
CaO	%	9.13	4.48	2.56	3.57	2.75
MgO	%	2.46	1.81	0.53	2.38	0.75
K_2O	%	1.14	0.48	nm	0.21	0.66
Na_2O	%	1.73	0.69	nm	1.09	0.068
MnO_2	%	0.038	0.20	nm	nm	nm
SO_3	%	0.82	nt	nm	nm	nm
P_2O_5	%	0.24	nt	nm	0.10	0.44
TiO_2	%	1.25	0.13	nm	nm	1.66
CuO	ppm	nm	nm	11.1	nm	nm
MnO	ppm	nm	nm	1263	nm	470
CdO	ppm	nm	nm	0.27	nm	nm
PbO	ppm	nm	nm	7.60	nm	nm
As_2O_3	ppm	nm	nm	<0.0001	nm	nm
Cr_2O_3	%	nm	nm	nm	nm	0.050
NiO	%	nm	nm	nm	nm	0.012
pH		nm	nm	nm	9.91	10
Electric Conductivity (EC)	dSm^{-1}	nm	nm	nm	nm	0.24
Calcium Carbonate Equivalent (CCE)	%	nm	nm	nm	nm	10

Note: a: CFA identification [21]
b,c,d: CFA for soil amendment [22–24]
nt: not detected
nm: not measured

3 CFA effects on soil physical property

The incorporation of CFA into soil has positive effects on soil physical properties, particularly in too sandy or clayey soils. Adriano and Webber [25] noted that silt-sized particles in CFA make it a viable substitute for topsoil, enhancing water retention in surface mine lands. This modification of soil fractions leads to enhanced aggregation and infiltration [9]. Textural improvements also impact soil aeration. Furthermore, Chang et al. [26] discovered increased hydraulic conductivity with CFA application, reducing soil surface crusting. Hydraulic conductivity decreases when more than 20% CFA (by volume) is added to calcareous soils or more than 10% to acidic soils. This decline results from the pozzolanic reaction of CFA, binding soil particles when wet, reducing water flow. Interestingly, the pozzolanic effect is more pronounced in acidic soils, although the mechanism is not fully understood.

Table 2. CFA effects on selected soil quality physical parameters [12].

Soil quality parameters	**Value for measurement in agricultural soil**	**Soil amended with**		**Crops**
		Decomposed ash	**Fresh ash**	
Bulk density	1.3 g cm^{-3}	Decrease than 1.3 g cm^{-3}	Decrease than 1.3 g cm^{-3}	Soybean, barley
Aeration	High	Increase	Increase	Grass
Water retention (whc)	High	Increase	Increase	Corn
Plant available water	High	Zero to minimal effect	Zero to minimal effect	Horticultural crops (carrot, radish, beet, lettuce)
Hydraulic conductivity	High	Rise by minimal dose	Rise by minimal dose	Barley
Modulus of rupture	High	Decrease	Decrease	Barley

Table 2 confirmed CFA application has impact on the physical properties of soil. Fail and Wochok [27] reported that the augmented growth of soybeans treated with CFA were directly associated with alterations in soil texture and an enhancement in water-holding capacity. Such modifications in soil texture subsequently influence other physical parameters such as water-holding capacity, bulk density, and soil porosity. In the context of the Barley cropping system, Chang et al. [26] stipulated that an enhancement in water-holding capacity was exclusively observed when CFA was applied at concentrations exceeding 25%. This specific dosage was also found to lower the soil's bulk density. It is noteworthy to mention that an increase in water-holding capacity does not unequivocally correlate with an elevation in plant-available water.

High CFA application rates (up to 560 and 1120 t ha^{-1}) significantly improve water-holding capacity but should be used cautiously due to potential negative impacts on other soil properties (Table 3) [25]. One adverse consequence includes an escalation in the soil electrical conductivity (EC) [15], attributed to an excessive influx of soluble salts. Table 3 shows that applying CFA to sandy soils can lead to heightened levels of EC. This increase in EC can subsequently reduce the soil's water-holding capacity due to elevated osmotic pressure. Additionally, CFA application lowers the modulus of rupture, affecting soil particle cohesiveness, potentially impacting soil structure and stability [12,26].

Table 3. CFA doses and its impact on sandy soil [15].

Treatments combination	CFA dose	Soil texture	Results of observations
CFA+soil	0, 10, 20, 30, 40% (ww^{-1})	Clayey, sandy clay loam, sandy, sandy loam	Incorporating CFA into soils with varying textures alters both the physical and physico-chemical conditions of the soil. The changes can subsequently impact crop production. Hydraulic conductivity is decreased by 25%, while soil water retention is enhanced.
CFA+soil	0, 280, 560, 1120 t ha^{-1}	-	Enhanced soil physical characteristics (capacity to hold water, water available for plant uptake, ability to retain moisture).
CFA+soil	0, 1, 2.5, 5, 10 and 15 t ha^{-1}	Sandy, sandy loam	Enhanced soil physical characteristics and increased rice growth and yield at 10 tha^{-1} CFA dose.
CFA+soil	0, 3, 6, 12 and 30% (ww^{-1}) dry weight basis	Sandy, sandy loam	The increased electrical conductivity might limit the soil's capacity to hold water due to higher osmotic pressure.

4 Reuse/recycle CFA as waste management strategy and to mitigate climate change

Reuse/Recycle CFA as waste management is imperative, particularly within the Indonesian framework where CFA is no longer classified hazardous-toxic waste. Given its substantial production volumes at both national and global scales, CFA serves as an economically valuable resource. Moreover, CFA application as a soil amendment is correlated with carbon sequestration capacity in soil [28]. Specifically, the incorporation of CFA into soil leads to improvements in soil properties, subsequently augmenting the soil ability to sequester carbon. This mechanistic pathway elucidates that CFA, acting as a soil amendment, elevates soil productivity, which in turn boosts plant yield. This leads to an increase in soil carbon stocks, facilitated by an optimized environment and enhanced root growth.

Above ground, the improved plant growth results in higher biomass production, which, when returned to the soil, can maintain or even increase current carbon stocks. The concentration of C stocks depends on variables like biomass turnover and decomposition rates. Ukwattage et al. [28] posits that the introduction of organic carbon with extended residence time (recalcitrant) into the soil is requisite for effective climate change mitigation and adaptation. According to Amonette et al. [29], the presence Fe oxide in alkaline CFA has the capability to stabilize the tyrosinase enzyme, thereby augmenting the humification process. Furthermore, alkaline nature and Fe oxide fractions within CFA are contributory factors in enhancing humification.

Palumbo et al. [30] delineates that one way for stabilizing soil organic C involves a chemical stabilization process, particularly when labile organic materials are complexes with clay minerals via polyvalent cation bridges. Subsequent soil aggregation offer additional physical protection to organic C, when organic C was covered and adsorbed by soil aggregate. Moreover, Yunusa et al. [31] identifies the role of unburnt carbon and cenosphere particles in carbon adsorption. The two components serve as the primary adsorbents in CFA. Dissolved organic matter (DOM) is anticipated to be effectively adsorbed by cenospheric particle of CFA. Yunusa et al. [31] also notes that the application of alkaline CFA mitigated carbon loss by up to 36%, while acidic CFA reduced total C loss threefold.

5 Conclusions

The enactment of Government Regulation No. 22/2021 represents an innovative policy intervention by the Indonesian government. The removal of coal fly ash bottom ash from the hazardous-toxic waste classification is anticipated to increase the rate of coal fly ash bottom ash utilization especially as soil amendment. CFA is a promising soil amendment, enhancing soil nutrient availability, thereby ameliorating soil fertility and promoting plant development, and also impacted positively on soil physical properties. In addition, Reuse/recycle CFA as an alternative to landfill disposal offers significant economic and environmental benefits, with its environmental consequences are thoroughly documented. Furthermore, utilizing biomass ash (including CFA) as a soil amendment and augmenting soil carbon reserves are effective approaches for mitigating climate change.

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