Provision of Standards to Support the Potential Utilisation of Fly Ash and Bottom Ash from Coal-Fired Power Plants for Wastewater Treatment

Hermawan Febriansyah
Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency

Teguh Pribadi Adinugroho
Research Centre for Testing Technology and Standards, National Research and Innovation Agency

Ellia Kristiningrum
Research Centre for Testing Technology and Standards, National Research and Innovation Agency

Danar Agus Susanto
Research Centre for Testing Technology and Standards, National Research and Innovation Agency

他

https://doi.org/10.5109/7326987

出版情報：Evergreen. 11 (4), pp.3520-3535, 2024-12. 九州大学グリーンテクノロジー研究教育センター
バージョン：

EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 11, Issue 04, pp3520-3535, December, 2024

Provision of Standards to Support the Potential Utilisation of Fly Ash and Bottom Ash from Coal-Fired Power Plants for Wastewater Treatment

Hermawan Febriansyah[1,*], Teguh Pribadi Adinugroho[2], Ellia Kristiningrum[2],
Danar Agus Susanto[2], Utari Ayuningtyas[1], Febrian Isharyadi[1], Ajun Tri Setyoko[2],
Meilinda Ayundyahrini[2]
[1]Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, South Tangerang, 15314, Indonesia
[2]Research Centre for Testing Technology and Standards, National Research and Innovation Agency, South Tangerang, 15314, Indonesia

*Author to whom correspondence should be addressed:
E-mail: hermawan.febriansyah@brin.go.id

(Received May 13, 2024; Revised September 2, 2024; Accepted November 26, 2024).

Abstract: Fly ash (FA) and bottom ash (BA) produced by coal combustion have environmental impacts. Besides its well-known use in construction and civil engineering, FABA can also be used as a substance for wastewater treatment (WWT). However, the characteristics of FABA depend on the coal source, combustion condition, and flue gas treatment. The qualities of a given utilization of FABA are better determined by standards based on research that later needs to be agreed upon by the stakeholders. This study aims to give a preliminary compilation of significant parameters for standards provision, especially for WWT. Standard parameters were considered from published peer-reviewed articles, a partial of the FACTS (Framework of Analysis Comparison and Testing of Standards) method. The study finds vital criteria for utilizing FABA in wastewater treatment, including unburnt carbon or loss of ignition (LOI), density/specific gravity, particle size, porosity, specific surface area, water holding capacity, CaO, and cenosphere content. A new work item for standard development is required due to the differences in parameters compared to the well-known and widely cited standard. Additional research is required to establish standardization of the parameters. The availability of standards supports the widespread utilization of FABA, especially for WWT.

Keywords: fly ash; bottom ash; coal; FABA standard; wastewater treatment; FACTS method

1. Introduction

Population growth is the primary driver of rising energy consumption[1)] and the expected increase in the gross domestic product (GDP)[2,3)]. Energy is used to power industries, offices, residences, transportation, etc., to boost the nation's GDP and provide comfort[4)]. The International Energy Agency (IEA) estimates that 2020 energy demand will have reached about 600 exajoules and is projected to increase by approximately 1% annually through 2030[5)]. To provide this amount of energy, about 80% of the energy source is still using fossil fuels, with the share of coal close to 30%. The proportion of coal may be even higher, reaching 38 or 40%[6)]. Coal is still a significant energy source worldwide, especially in the United States, China, and other Asian nations. According to the IEA World Energy's Net Zero Emissions (NZE) by 2050 model[7)], coal-fired energy will continue to be utilized until 2040. However, the coal complete phase-out by 2040 may take longer because the IEA's Tracking Clean Energy Progress (TCEP) to oversee the implementation of the NZE 2050 scenario, per July 2023, shows it needs to be on track[8)]. IEA's TCEP evaluates current advancements in more than fifty essential components of the energy system that are crucial for the transition to clean energy, including electric car sales and renewable electricity capacity additions.

With coal still used for decades to come, the urgency comes for the need for efforts to reduce coal-fired power generation's adverse environmental effects. Energy efficiency and environmental impact are currently issues that receive special attention[9,10)]. This is especially true in terms of sustainability[10)]. Mining, transportation, and coal combustion activities in power plants produced CO_2, CO, SO_x, NO_x, CH_4, NHMCs/VOCs, and particulate emissions[11)]. Coal combustion also generates solid wastes, such as fly ash (FA), bottom ash (BA), and gypsum, from the flue gas cleaning or desulfurization (FGC/FGD) process[12,13]. Worldwide Coal Combustion Products Network (WWCCPN) refers to these wastes as Coal Combustion Products (CCPs)[6]. To reduce environmental impact, adding value to CCPs into products or different kinds of utilisations is crucial[14,15]. In 2016, FA and BA (FABA) accounted for 64% of global CCP production of 1.2 billion metric tonnes, while foreign commerce in 2015 was estimated at 5 metric tonnes[6].

If not handled properly, large amounts of FABA due to CCP will potentially cause environmental problems[16]. FA is a fine fraction of CCP in the form of particles separated from the gas flow outside the combustion chamber to avoid emissions into the atmosphere[17]. FA consists of an inorganic fraction and a small part of organic substances (unburned carbon). It is a finely ground powder comprising siliceous and aluminous compositions, capable of forming a compound with binding properties when mixed with water and lime[18,19]. Meanwhile, BA is a coarse fraction of CCP produced in the combustion chamber due to burning coal that burns completely or partially[20]. BA consists of sand particles, especially quartz, mixed with mineral impurities contained in coal[21].

Furthermore, bottom ash has been discovered to improve the load-bearing capacity of soft soil when utilized as an alternative material in granular columns[22]. To minimize the negative impact of FABA, reuse of FABA as raw materials has been carried out. Large amounts of FABA are currently used as building materials and in geotechnical applications in the construction sector[6,23–25] because FABA is ideal for hardened or solidified materials[23]. FABA utilization depends on the chemical and mineralogical characteristics, which vary based on coal's intrinsic properties (mineralogy dependent on coal source), burning condition (facility type, combustion temperature, length of time in the furnace, etc.), flue gas treatment, collection method and period, and deposit duration[26,27].

Another potential utility besides building materials is that FABA can be used in wastewater treatment. Wastewater arises due to industrial activities or daily domestic activities[28]. If not appropriately managed, wastewater can pollute the surrounding environment, especially the quality and ecosystem of water[29–31]. The primary source is industrial activity, which also produces wastewater containing dangerous pollutants, including heavy metals and dangerous organic compounds that are byproducts of the production process[29,30,32,33]. Based on the composition of FABA, several studies have reported that FABA can be used in wastewater treatment[34–37]. Generally, the functionalization of FABA in wastewater treatment is an adsorbent for several hazardous pollutants in wastewater. The application mechanism of FABA as an adsorbent in wastewater is about how this material attracts and absorbs harmful compounds from wastewater, helping to clean it and keep the environment healthy. Adsorption mechanisms occur on the surface in chelation, ion exchange, or complex formation (Fig. 1).

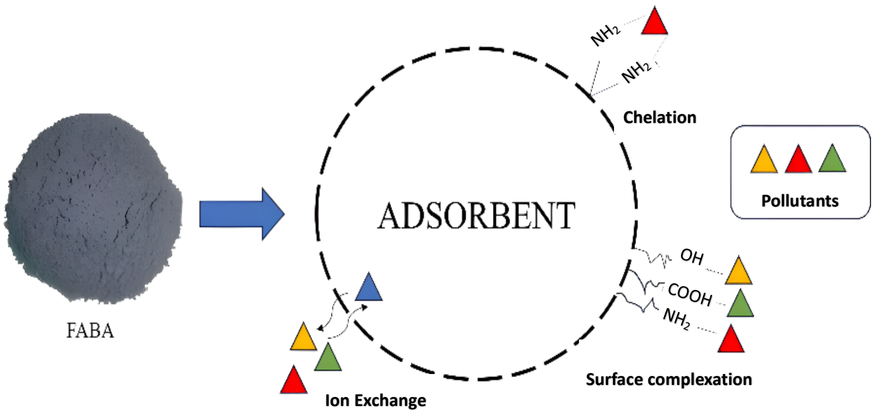

Fig. 1: Illustration of the mechanism of application of FABA as an adsorbent in wastewater.

The unique inherent qualities influence the application of FABA as described earlier[23–25]. Regarding that matter, standards are needed for the potential wide application of FABA. Standardization is a crucial part of FABA applications. This primarily supports a steady characteristic of CCPs, which can promote consistent use and facilitate trade[6]. A standard document is a set of requirements, guidelines, and rules for a product, service, or process accepted by a recognized entity and developed by a consensus of stakeholders[38]. Implementing standards can provide benefits in increasing awareness of quality[39], quality improvement[40,41], increased productivity[39,41,42], protection of health, security, and safety aspects[43], and economic benefits[44–46]. In the case of the construction industry, various standards for pozzolan cement set the most important parameters with FA mixture are the content of SiO_2+Al_2O_3+Fe_2O_3, SO_3, CaO, SiO_2, lost on the ignition, and percent of water, along with physical characteristics of density, water demand ratio, and maximum particles amount retained by a 45 μm (No. 325) sieve[47]. Many standards were found for FA utilization in pozzolan cement, the application of which is for the construction industry. They are ASTM C 618 (US)[48)], JIS A 6201 (Japan)[49)], GB/T 1596 (China)[50)], and EN 450-1 (EU)[51)]. Other standards for FA in cement and concrete are AS/NZS 3582 (Australia/New Zealand), IS 3812-1 (India), and GOST 25818 (Russia). Indonesia adopted ASTM C 618-08a into SNI 2460:2014[52)].

Other standards to facilitate FABA application in other fields are scarce, even though many applications for FABA are shown in various published research papers. This study aims to evaluate published articles and identify the essential characteristics of FABA applications for wastewater treatment. Studies with similar purposes in different fields, such as the work by Ayello and Lopes[53)], conducted a Systematic Literature Review (SLR) on implementing the IEC 61850 standard to propose a fresh approach to achieving interoperability in a setting with several vendors. Another example is the SLR study by de Frietas et al.[54)], in which they intended to give input for the standardized Function Point Analysis (FPA) method in software testing that is already widely adopted.

For novelty, this study continues the work of various reviews on FABA utilization from the perspective of standardization. The outcome can contribute to creating standards for the widespread utilization of FABA, which is expected to help mitigate the environmental effect of coal-based energy generation.

2. Methodology

This study was conducted by collecting various information derived from reviews and research papers related to the utilization of FABA using Scopus. Before searching the parameters, different applications of FABA are studied through review papers other than in the construction industry. Four review papers were found for FABA utilization Jayaranjan et al.[24)], Yao et al.[25)], Zhou et al.[26)], and Alterary & Marei[55)]. Three review papers are also specific to wastewater treatment, mentioned later in section 3.3.

Afterward, information is further explored and extracted using content analysis of the references in the review papers. At least 43 papers are used to gather the important parameters. This is meant to create abstracts of the required characteristic or important relevant parameters of particular use, which in the context of the study is for wastewater treatment, for input in standards development (workflow is given in Fig. 2). The papers used are taken from those published within a period of 10 years (2013 – 2023). This effort to gain initial knowledge and information of important product parameters for a certain utilization is a partial method of the FACTS (Framework of Analysis Comparison and Testing of Standards)[56)], a tool for developing and maintaining standards. The method has been used or considered in research to determine the technical parameters of various products in different fields, such as to develop standards for electric vehicle batteries and battery management systems, wheelchairs, and aerospace. The studies referenced include those by Aristyawati et al.[57)], Sutopo et al.[58)], Pratiwi et al.[59)], and Sanya and Shehab[60)].

3. Result and Discussion

3.1 Variation of FABA chemical composition

Fly ash and bottom ash are byproducts produced from coal combustion[61)]. Fly ash is a fine powder residue that is removed from the combustion chamber by the exhaust gases after pulverized coal is burned[62)], and bottom ash is the larger and heavier particles that are left behind at the bottom of the combustion chamber after coal combustion (generally composed of non-combustible materials that do not burn during the combustion process)[63)]. As a result of coal combusting, fly ash, and bottom ash have similar compositions but with different amounts of content[35)]. Fly ash and bottom ash are dominantly composed of silica, aluminium, iron, calcium, and oxygen and contain many other elements at trace levels. Heavy metals such as arsenic, cadmium, chromium, and lead[62)].

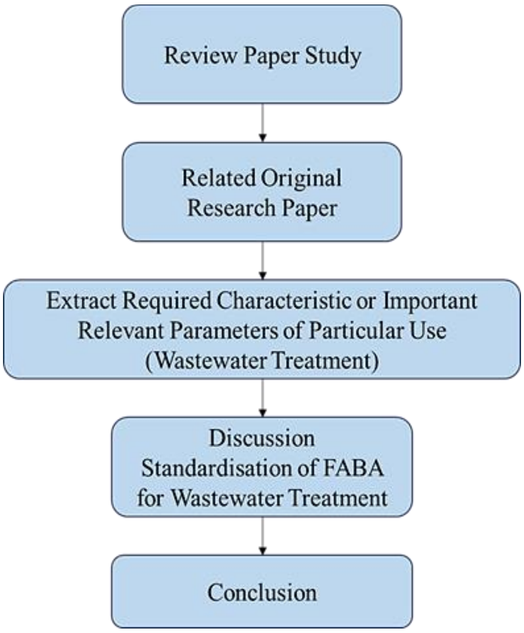

Fig. 2: Workflow of the study.

Research results show that differences in the physiochemical properties of fly ash and bottom ash depend on several factors. First, the kind and source of the coal affect the characteristics of coal fly ash and bottom ash. Coal comes in four different varieties: lignite, bituminous, sub-bituminous, and anthracite. The kinds and quantities of carbon, the thermal energy the coal can generate, the moisture content of the carbon, and other chemical components all affect the type of coal[61,64)]. The concentrations of silica oxide (SiO_2), alumina oxide (Al_2O_3), and ferric oxide (Fe_2O_3) vary throughout the different varieties of coal[65)]. Other than that, the physical and chemical properties of coal ash are dependent on the combustion process and power plant design[66)], especially the differences in leaching procedures and methods, boiler types, the coal combustion temperature, the furnace's burning conditions, ash managing performances, and utilized processing technologies in coal-fired power plants[61]. Chang and Wey (67) also reported[67]that different types of incineration processes cause significant differences in the properties of bottom and fly ashes. The cause of the difference lies in the different characteristics of ashes due to the transportation and mixing system inside the furnace. A recap of variations in the general chemical composition of FABA is given in Table 1.

3.2 Various FABA utilization

Various FABA utilization has been reported in several studies, especially in construction, agriculture, ceramic manufacturing, wastewater treatment, and other uses (Table 2). An optimal utilization hierarchy of FABA can be suggested considering the valuable contents, significant elements, and the hazards in utilizing it[68]. FABA utilization can start from the extraction of valuable elements, followed by synthesis to another form like zeolite, and utilization in wastewater treatment. These utilisations still have second pollution or environmental risk concerns[24,69]. Like in ceramic and construction, utilization can close the chain because FABA is utilized by solidification and stabilization, which can prevent further pollution. Similar hierarchical utilization was put forward by Srivastava et al.[70] by recommending metal-loaded used bagasse FA to create fire briquettes and that the bottom ash produced be combined with concrete to be used in the building. Studies to gather important parameters can trigger the work of standards to support various uses of FABA described earlier. In that context, a focus area can be selected, as is intended to be done in this study, namely proposing an abstract of standard parameters for FABA utilisations in wastewater treatment. The utilization has the potential to use FABA in large amounts.

3.3 FABA utilization for wastewater treatment

FA and BA can be used for wastewater treatment (WWT)[23]. The radiological characteristics of FABA do not affect the characteristics of treated wastewater. Therefore, FABA is safe to use for treating wastewater and does not present a substantial radioactive danger.[71]. However, coal FA is used more for WWT than BA. Specific literature for FA utilization in wastewater can be found in Gadore and Ahmaruzzaman[72], Mushtaq et al.[73], and Singh et al.[69]. FA can help WWT by physical and chemical methods (Table 3). Physical includes adsorption, filtration, and coagulation; chemical includes photocatalysis and Fenton process[73]. By adsorption, many contaminants, including phenol, dyes, medications, pesticides, heavy metal ions, detergent, fluoride, phosphate, and others, can be eliminated from wastewater with FA[74-76]. Because of its high porosity, huge surface area, microscopic particle size, and unburnt carbon, FA is an excellent low-cost adsorbent for removing harmful contaminants from wastewater. The oxides in FA include alumina (Al_2O_3), silica (SiO_2), calcium oxide (CaO), and iron oxides (Fe_2O_3). They absorb hazardous heavy metals from wastewater, and FA's alkaline nature confers a neutralizing characteristic[69,72]. FA can also be applied as a medium to make permeable reactive barriers (PRBs)[77]. PRBs are a passive processing technology for water source recovery in the form of in situ permeable reactive barrier walls (which will be installed directly in acid mine water reservoirs or sumps) which react with certain metal elements and function to reduce or eliminate dangerous heavy metal contaminant elements in the water. Acid mine drainage passes through it so that the resulting water can safely be released back into the environment. FA does not cause dangerous contaminants in the water treatment process[78].

Similar to coal FA, coal BA is known for its chemical composition, which is rich in silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3). BA has various advantageous qualities in addition to its chemical makeup, including surface area, porosity, particle size, and water-holding capacity. Coal BA has a good adsorption capacity for copper and reduces chemical oxygen demand (COD) and the concentration of various pollutants[36]. Coal BA can also be used for domestic and industrial wastewater treatment. Furthermore, coal BA can be used as a potential adsorbent to remove toxic dyes in tannery waste processing by reducing the concentration of COD parameters[23,79]. Coal BA can also be used to remove H_2S from waste gas or to reduce the concentration of various pollutants in leachate[80]. Apart from that, coal BA can also be used to remediate water/wastewater from phosphate.

Besides FA and BA, other materials have the same function with several advantages and disadvantages. Al_2O_3-NaAs zeolite composite hollow fiber membrane is used for filtration and is very effective at removing PB, but the NaAs zeolite composite membrane is very difficult to characterize with XRD because hollow fibers are too thin to detect. Granular activated carbon (GAC) using the adsorption method can be used as an odor barrier because it has a high surface area and porosity. However, in its application, the temperature parameters must be increased twofold to obtain optimal surface area and pore volume values. FE oxidation uses the Fenton process, an optimal process that can effectively degrade various types of organic pollutants but has high costs and risks in its application (Table 4).

The use of BA is a cost-effective and environmentally friendly alternative to recover water from phosphate in the presence of competing ions (humic acid)[81]. Coal BA can also reduce Boron in ceramic industry waste; the use of BA and long-chain polymers or flocculants in the adsorption-flocculation mechanism can remove up to 80% of boron under optimum conditions (pH ¼ 8.0, dose ¼ 40-gram bottom ash/300 mL wastewater, residence time ¼ 1 hour)[82]. Furthermore, some other applications of BA are in processing expired medicinal waste[83], improving wastewater quality as a waste disposal option for industry[84], and removing Cd and Ni from simulated acidic wastewater[85].

3.4 Review of required parameters – FABA utilization in wastewater treatment

As mentioned in the previous chapter, other standards can be considered in addition to ASTM C618: CSA A3001, EN 450-1, AS/NZS3582.1. These four standards have broadly identical specifications, but there are differences in LOI limitations due to differences in coal properties and combustion processes. CSA A3001 is a fly ash classification specification standard that applies in Canada. EN 450-1 is a standard fly ash specification, generally mixed in cement in European countries. This standard is different from ASTM C618, which classifies materials based on LOI Limits rather than CaO content. Meanwhile, AS/NZS 3582.1 defines fly ash, LOI, and SAI-special grade specifications.

Table 1. Variation in the general chemical composition of FABA (% weight).

Compositions	**FA**		**BA**		**Unspecified FABA**	
	Malaysia[61]	**Indonesia[86]**	**Malaysia[61]**	**Indonesia[86]**	**China[87]**	**China[88]**
SiO_2	47.6	61,63	45.3	45.59	34.5	41.23
Al_2O_3	23.8	17,71	18.1	27.06	18.8	31.54
Fe_2O_3	7.4	9,30	19.84	6.87	16.0	3.94
$SiO_2+Al_2O_3+Fe_2O_3$	78.82	88,64	83.24	NA	69,3	NA
CaO	10.7	4,24	8.70	6.87	17.7	10.65
MgO	1.5	1,98	0.69	1.94	1.8	0.41
Na_2O	2.1	1,31	NA	4.97	0.5	0.21
K_2O	1.4	1,28	2.48	0.78	0.3	1
TiO_2	2.92	NA	3.27	NA	0.6	2.45
P_2O_5	1.16	NA	0.351	NA	NA	2.561
MnO	0.12	NA	0.248	NA	NA	NA
SO_3	0.73	2,83	0.3	1.73	7.9	2.79
BaO	0.1	NA	0.311	NA	NA	NA
LoI	0.43	4,27	0.1	3.35	NA	NA

Table 2. Utilization of FABA.

Utilization	**FA**	**BA**	**The main consideration factor**	**Reference**
Construction	√	√	- More cost-effective compared to soil as construction material. - Enhance soil characteristics and functions as a stabilizing agent and engineering characteristics of soft soils, including strength, bearing capacity, and reducing displacement. - Pozzolanic characteristics render it valuable as a concrete alternative for cement and various construction uses. - Enhance the plasticity and minimize the exudation of freshly mixed concrete. - Decrease the heat generated during the hydration process, reducing the likelihood of early-stage cracking in concrete. - Boost concrete's long-term durability properties. Improves the strength, durability, and microstructural characteristics of concrete. - We are promoting cleaner manufacturing by mitigating greenhouse gas emissions and conserving natural river sand in the concrete production process.	Jayaranjan et al.[23], Yao et al.[24] , Zhou et al.[25] , Mahale et al.[89]
Agriculture	√	√	- An alternative to using dolomite and lime in crops that is economical and ecologically sustainable. - Boost plant nutrient availability, except organic C and N - Enhance the physiochemical and biological characteristics of soils and provide plants with easily obtainable macro- and micronutrients. - Improve the activity of microbes by enhancing the structure of the soil, lowering pH, and serving as a substrate for the growth of microorganisms. - Boost the output of biomass from plants in deteriorated soils. Several elements released into the soil can benefit crop yield and plant growth. - Heavy metal immobilization in contaminated soils can increase the fertilization rate.	Yao et al.[24], Zhou et al.[25], Mahale et al.[89], Lee et al.[90], Jala et al.[91], Agustini et al.[92], Trung Phan et al.[93]

Utilization	FA	BA	The main consideration factor	Reference
			- Enhance the seed germination rate.	
Geopolymer	√		- Solid adsorbents.	Yao et al.24), Han et al.94)
Ceramic industry	√	√	- Blend with stoneware clay to produce superior physical and mechanical properties by modifying the ceramic body's composition and adapting the heating process to counter adverse traits. - They exhibit significant crystallinity, boast a thermal expansion coefficient, and directly influence ceramic composite properties like density, absorbency, porosity, and firing compression strength.	Jayaranjan et al.23), Yao et al.24), Zhou et al.25), Zhang et al.95), Namkane et al.96)
Water and wastewater treatment	√	√	- Potential adsorbent to remove organic pollutants, heavy metals, and other contaminants so wastewater processed by a WWTP and meets environmental quality standards can be safely disposed of into water bodies.	Yao et al.24), Zhou et al.25), Lin et al.36), Labidi et al.37), Alterary & Marei55), Nollet et al.97), Visa et al.98), Mushtaq et al.73), Attari et al.99), Chang et al.100), El Mouhri et al.79)
Energy catalysis	√	√	- The high content of iron oxides - High thermal stability - Pollutant removal, low cost, high lifespan, and applicable without pretreatment	Yao et al.24), Zhou et al.25), Goembira et al.101)
Zeolite	√		- Precursor of natural zeolites - Zeolites made from waste fly ash can be utilized in commercial operations for CO collection and could be a cheap, feasible technique for creating vast amounts of adsorbent.	Yao et al.24), Langauer et al. 102), Yadav et al. 103)
Material synthesis	√	√	- A substance that acts as a catalyst for reactions in the liquid, solid, and gas phase precursor for material synthesis	Yao et al.24), Zhou et al.25), Belviso et al.104), Shaila et al.105), Han et al.94)

Table 3. Utilization of FABA in wastewater treatment.

Type	FA	BA
Function - Physical - chemical	adsorption, filtration, and coagulation photocatalysis and Fenton process	Adsorption
Utilization	a medium to make permeable reactive barriers (PRBs)	- A potential adsorbent to remove toxic dyes in tannery waste processing by reducing the concentration of COD parameter. - To remove H_2S from waste gas or to reduce the concentration of various pollutants in leachate. - For remediating water/wastewater from phosphate. - to reduce Boron in ceramic industry waste. - to remove Cd and Ni from simulated acidic wastewater.

Table 4. Other materials for WWT with the advantages and disadvantages.

No	Material Name	Physics Method*			Chemicals Method*		Advantage	Disadvantage	Ref.
		A	C	F	P	Fe			
1.	Activated Bottom Ash	√					Can act as an effective adsorbent to remove dangerous azo dyes from textile industry wastewater, namely metanil yellow and methyl orange.	Preparing bottom ash as an adsorbent involves steps such as cleaning, drying, and activation, which require additional time and costs.	106)
2.	Al_2O_3-NaA zeolite composite hollow fiber membranes			√			The testing findings showed the porous membrane's remarkable effectiveness in removing Pb (II) (more than 99%), and the primary mechanism of Pb (II) removal was described as metal adsorption on the membrane surface.	NaAs zeolite composite membranes are very difficult to characterize by XRD because the hollow fibers were too thin to be detected	107)
3.	TiO nanofiber membrane on porous fly ash ceramic (TNM-PFACS)	√			√		The membrane can remove of heavy metal ions Cu (II), Cd (II), and Cr (VI)) and rhodamine B	The adsorption capacity of TNM-PFACS is small compared to TiO_2 and TiO_2 composite powder.	109)
4	Granular activated carbon (GAC)	√					GAC was used as an adsorbent and was regenerated thermally oxidatively to obtain more efficient and cleaner results. GAC is an odor barrier with a high surface area and porosity. The result is regeneration at a temperature of 900 ^{0}C using an inert atmosphere, producing GAC with optimized textural properties because it provides the highest surface area value.	In this case, the critical factor is temperature, which must be doubled to obtain the surface area and pore volume values.	110)
5	Ferromagnetite (F) and eggshells (E) Coagulants		√				FE coagulants produce rapid particle aggregation and larger floc sizes, so they are recommended for improving flocculation and sedimentation in the wastewater treatment process.	To remove parameters such as turbidity, color, and total suspended solids.	111)
6	Fe oxidation					√	High degradation rates and effective removal of various types of organic pollutants	The narrow working pH range, the high costs and risks associated with handling, transporting, and storing reagents (H_2O_2 and catalyst), and the significant iron sludge.	112)
Remarks: A: Adsorption; C: Coagulation; F: Filtration; P: Photocatalysis/Photodegradation; Fe: Fenton process									

It can be challenging to compare fly ash specifications across many standards since various standards have varied requirements for conducting tests like LOI. The primary distinctions between the fly ash requirements included in ASTM C618 and CSA A3001, EN 450-1, and AS/NZS 3582.1 are related to the fly ash's physical characteristics, chemical composition, categorization limitations, testing procedures, and performance standards.

Fly ash is subject to ASTM C618's chemical composition restrictions, including sulfate concentration specifications, calcium oxide (CaO), and loss of ignition (LOI). ASTM C618 sets a chemical composition restriction different from CSA A3001 and AS/NZS 3582.1. Fly ash must meet the specific chemical composition standards of EN 450-1. differs from ASTM C618 in terms of its chemical composition limitations.

Variations in criteria for physical qualities, including fineness, specific gravity, and water content, can contribute to disparities in physical attributes. Varied approaches to testing and assessing the qualities of fly ash also led to varied interpretations of the results in various standards. The performance parameters used in each standard manufacturer's specification to determine if fly ash is suitable for a particular application vary, which affects the end product's quality and attributes[108)] (Table 5).

Most FABA is composed of CaO, SiO_2, Al_2O_3, and Fe_2O_3. The three last compounds decrease as CaO rises. The commonly referred ASTM standard defines explicitly the % weight combination of SiO_2+Al_2O_3+Fe_2O_3 as the important characteristic for concrete instead of the CaO content for the coal ash classes. Even though both parameters can be used, CaO is considered a more important parameter in WWT use; thus, the essential parameter in the standard should be switched to prescribe CaO. Alkalis also rise with CaO, including Na_2O and K_2O, as well as SO_3[55)].

Adsorption is the best wastewater treatment method available for use in industrial settings. This method's capacity to eliminate harmful substances[55,109,110)], cheap running costs, and straightforward design make it a desirable one[79,111)]. The use for removing pollutants from wastewater by coal FABA refers to the fact that FABA is a material widely available at low cost and can replace activated carbon[79)]. For two reasons for WWT by adsorption, coal ash from lignite or sub-bituminous coal is preferred. First, it utilizes the higher ash production from the low calorific value coals (lignite or sub-bituminous)[72)]. Second, the high CaO content improved the adsorbent function, which benefits water remediation[23,72)]. However, the review from Singh et al.[69)] and Mushtaq et al.[73)] described class F as mainly used over class C FA. Mostly, the terminology of coal ash classes and primary reference of parameters in published articles are taken from the ASTM C 618-3 standard specification for coal ash for use in concrete. To see CaO content according to the coal types, side-by-side comparison tables of FABA major elemental composition from different coal sources can be seen in Jayaranjan[23)] and Gadore & Ahmaruzzaman[72)].

Another component of coal ash is the cenosphere. The cenosphere is one of the fractions in ash coal[112)], and the geosphere is physically spherical, has low density, and is inert[113)]. Various products, including refractory materials, bricks, cement, and concrete, can be made using cenosphere[113)], cenosphere can also be applied in WWT[114,115)]. This can happen because the components contained in the cenosphere are in the form of several metal oxide compounds[113,116)]. Several applications of metal oxide compounds have been carried out in WWT to minimize the existing pollutant content[117–119)]; therefore, the higher cenosphere content in coal ash can optimize the WWT process.

With the matching characteristics described earlier for WWT – which are the high porosity, large surface area, microscopic particle size, water holding capacity, content of unburnt carbon and oxides, alkaline nature, and cenosphere, the essential coal ash parameters gathered from the reviews specific to WWT are then given in Table 6. The scope of the standard is ash from coal, class C coal ash, and the intended use for WWT with adsorption needs to be described. The parameter composition differs from the ASTM standard for fly ash in concrete; thus, a new work item for standard development is needed. Even though WWT by adsorption using FA has been broad and known for two decades ago, its application in WWT is still inadequate[73)]. Meanwhile, FA-transformed materials like zeolite and geopolymer are subjected to other standards.

The iron and carbon contents can be used to estimate the density of FA. As C content rises, its density falls, and as Fe content rises, so does its density. The carbon content impacts the water requirement and workability of FA. Calculating the loss on ignition (LOI) allows for determining the differences in carbon content[24,55)]. When more unburnt carbon is present, the LOI is higher[55)]. To highlight another distinct need between FA for concrete and WWT, a high content of unburnt carbon is not wanted in concrete[25)] (or not exceeding 20%)[120)] because of reducing compressive strength; then an effort for carbon separation is needed[121)].

On the other hand, carbon's excellent adsorption characteristic is wanted in WWT[55,69,72)]. This emphasizes the need for a distinct standard for FA utilization in WWT. Some of these parameters are interrelated: density or specific gravity related to the existence of voids[25)], density is related to C content, C is related to LOI[55)], and water absorption can indicate the degree of porosity and specific surface area affected by LOI[25)]. To avoid unnecessary overlap, determining which main parameters influence the standard most requires further research and discussion.

Table 5. Comparison of fly ash parameters in ASTM C618, CSA A3001, EN 450-1, AS/NZS 3582.1.

Parameters	ASTM C618	CSA A3001	EN 450-1	AS/NZS 3582.1
Class of fly ash	F, C	F, CI, CH	A, B, C, N, S	Special, 1, 2
CaO (%)	≤18 or >18	<15, 15-20, >20	-	-
SiO_2+Al_2O_3+Fe_2O_3 (%)	>50	-	>70	>60 or >70
SiO_2 (%)	-	-	-	-
SO_2 (%)	<5	<5	<3	<3
Moisture content (%)	<3	<3	-	<5
LOI (%)	<6	<6, <8	≤5, ≤7, ≤9	<3, <4, <6
Retain on 45 μm sieve (%)	<34	<34	≤12, ≤40	<15, <25, <45
Strength activity, 7 days, %	>75	Optimal	-	
Strength activity, 28days, %	>75	Optimal	≥75	>75, >105
Strength activity, 91days, %	-	Optimal	≥85	-
Water requirement, %	<105	-	≤95	-

Source: Suraneni et al.107)

Table 6. Abstract of standard parameters – FABA for wastewater treatment.

Abstract for standard parameters		Comparison with ASTM C 618-03	Remarks
Parameters	**Direction of requirements**		
Unburnt carbon or Loss of Ignition (LOI)	Higher C better	LOI, max, %	Ash from coal lignite or sub-bituminous coal combustion, with intended use for wastewater treatment by adsorption
Density / specific gravity	Lower better	Max. % variation from average	
Particle size	Smaller better	Fineness, 45μm	
Porosity	Higher better	n/a	
Specific surface area	Higher better	n/a	
Water holding capacity	Higher better	Water requirement	
CaO	Higher better	n/a	
Cenospheres	Higher better	n/a	

3.5 Further research toward standardization of FABA for wastewater treatment

Efforts to review studies of FA as an adsorbent in wastewater have already been worked out by Wang & Wu122) and Ahmaruzzaman123), even before 2010. However, the intention is for something other than standardization. Those examples and the studies in different fields mentioned earlier in the introduction show that such studies are usually outside the intention for standardization. This indicates that comprehensive efforts of downstream research and innovation results through standardization are less recognized among researchers. At the same time, it is important because the review approach can be utilized as an initiative of a new standard or input for standard revision. Thus, it may provide an apparent reference, the enabler for mass production, and enhance the effectiveness of the industry/user.

Underlining relevant notes by Gadore and Ahmaruzzaman72) related to the topic of this study, it was described that more research must be done for the adsorption system in WWT to have practical uses at the industrial level. The new low-cost fly ash-based adsorbents should be tested using actual wastewater; reproducibility of adsorption data is crucial, and the adsorbent must be chemically and physically stable. In standardized FABA, the original FABA may be subjected to various preliminary treatments. Achieving the required or efficient formulation for WWT may involve the analysis of FABA characteristics81), mechanical activation, chemical modification, impregnation, and high-temperature calcination for enhanced performance73). Crushing, grinding, sieving, gasification, and pyrolysis are also suggested to remove toxic elements and enhance basic properties25).

Moreover, the utilization must be prudently related to the hazard of using FABA and the likelihood of heavy metal content124) that would contaminate the environment. Thus, the limit and procedure of application may need to be prescribed according to the standard or a separate standard. Those notes emphasize the need for different standards and further studies.

In this study, it is also known that parameters can influence each other. Therefore, the relationship between one variable and several other variables must be determined. For that purpose, a regression analysis which is a statistical method to investigate the relationship can be used and is common in many scientific fields such as financial data analysis, medicine, biology, agriculture, economics, engineering, sociology, geology, and others125). Copula can also be used because it has the main advantage of no restrictions on the probability distribution125). Copula provides flexibility in describing the dependence structure of bivariate meta-analysis126).

Furthermore, in the development of standards, consensus is usually used to determine the parameters. However, this is prone to subjectivity, so the determination of parameters in a committee meeting often has political nuances and lobbying even though it determines technical matters. Therefore, in determining choices by experts in their fields, statistical methods such as AHP or fuzzy AHP[127,128)] and ANP[129)] can be used.

A standard is a technical requirement that combines the protocols and techniques created with the consent of all involved parties, taking into account the requirements for science, technology, safety, security, health, and the environment, as well as current and upcoming improvements to maximize benefit[130-132)]. A specific limit for each essential parameter must be set according to statistical rules based on multiple FABA samples and experiments, effectiveness in the utilization (practicability or applicability), and environmental and economic considerations.

4. Conclusion

Review studies are available to recommend the use of a material, propose a method, or serve another purpose. However, the studies often aim for something other than standardization, which is important for downstream research and innovation results. Research is important as a basis for standardization, and significant parameters or proven best practices need to be made explicit and clear to users.

Essential standard parameters can be gathered from review papers for FABA utilization in wastewater treatment. The essential standard parameters for FABA utilization in wastewater treatment are unburnt carbon or loss of ignition (LOI), density/specific gravity, particle size, porosity, specific surface area, water holding capacity, CaO, and cenosphere content. The parameters differ from those in the existing well-known and broad-referenced standard, which has the intended scope of use being concrete. However, the specific values, only the direction, still cannot be given. A new work item for standard development is needed.

Further research is needed toward standardization of the parameters and to provide a reliable process at the industrial level, which may need multiple tests on various FABA samples in an actual application. Furthermore, the application procedure must be prescribed to protect the environment from unwanted negative impacts. FABA utilization in different fields needs distinct requirements. The requirements are manifested from research that provides scientific-based evidence and best practices. The standard helps to set the requirements to support industrial needs and facilitate trade. The expected outcome is a higher FABA utilization that can help mitigate the impact of coal-fuelled energy production.

Acknowledgments

The authors are grateful to the Research Centre for Sustainable Production System and Life Cycle Assessment and the Research Centre for Testing Technology and Standard, National Research and Innovation Agency of Indonesia, for their support in implementing this research.

Nomenclature

Al_2O_3	Aluminium oxide (alumina)
AS	Australian Standard
ASTM	American Society for Testing Material
C	Carbon
CaO	Calcium oxide
Cd	Cadmium
EN	European Norm
EU	European Union
Fe_2O_3	Iron (III) oxide or ferric oxide (magnetite)
GB	Guo Biao (The National Standards of the People's Republic of China)
GOST	Gosudarstvennyy Standard (international technical standards by the Euro-Asian Council for Standardization, Metrology and Certification - EASC, a regional standards organization operating under the auspices of the Commonwealth of Independent States)
H_2S	Hydrogen sulfide
IS	Indian Standard
JIS	Japanese Industrial Standard
K_2O	Potassium oxide
ml	milliliter
Na_2O	Sodium oxide
Ni	Nickel
NZS	New Zealand Standard
pH	Potential of Hydrogen
SiO_2	Silicon dioxide (silica)
SNI	Standar Nasional Indonesia (Indonesian national standard)
SO_3	Sulfur trioxide
US	United States
µm	micrometer

Greek symbols

%	percent

References

1) Bahman Zohuri, and Patrick Mc Daniel,

"Introduction to Energy Essentials: Insight into Nuclear, Renewable, and Non-Renewable Energies," Academic Press, (2021). doi:10.1016/ B978-0-323-90152-9.00001-3.

2) Matthaios Santamouris, "Energy Consumption and Environmental Quality of the Building Sector," in: M. Santamouris (Ed.), Minimizing Energy Consumption, Energy Poverty and Global and Local Climate Change in the Built Environment: Innovating to Zero, Elsevier, 29–64 (2019). doi:10.1016/b978-0-12-811417-9.00002-7.

3) Jürgen Scheffran, Miriam Felkers, and Rebecca Froese, "Economic Growth and the Global Energy Demand," in: A.A. Vertès, N. Qureshi, H.P. Blaschek, H. Yukawa (Eds.), Green Energy to Sustainability: Strategies for Global Industries, Wiley, 1–44 (2020). doi:10.1002/9781119152057.ch1.

4) T. Burandt, B. Xiong, K. Löffler, and P.-Y. Oei, "Decarbonizing china's energy system – modeling the transformation of the electricity, transportation, heat, and industrial sectors," Appl Energy, 255 113820 (2019). doi:10.1016/ j.apenergy.2019.113820.

5) International Energy Agency, "World Energy Outlook 2021," International Energy Agency, (2021). https://www.iea.org/reports/world-energy-outlook-2021. (accessed June 26, 2024)

6) D. Harris, C. Heidrich, and J. Feuerborn, "Global aspects on Coal Combustion Products," in: Proceedings of the World of Coal Ash (WOCA), St. Louis, MO, USA (2019), 2020: 25–33. https://www.vgb.org/vgbmultimedia/PT202010HARRIS-p-16422.pdf. (accessed June 26, 2024)

7) International Energy Agency, "World Energy Model Documentation," International Energy Agency, (2021). https://iea.blob.core.windows.net/assets/932ea201-0972-4231-8d81-356300e9fc43/WEM_Documentation_WEO2021.pdf (accessed June 26, 2024).

8) IEA, "Tracking Clean Energy Progress 2023," (2023). https://www.iea.org/energy-system/fossil-fuels/coal#tracking (accessed June 26, 2024).

9) K. Moroga, A. Nagata, Y. Kuriyama, T. Kobayashi, and K. Hasegawa, "State of implementation of environmental and energy policies adopted by the regional governments in japan," *Evergreen*, 2(2) 14–23 (2015). doi:10.5109/1544076.

10) T. Sato, "How is a sustainable society established? a case study of cities in japan and germany," *Evergreen*, 3(2) 25–35 (2016). doi:10.5109/ 1800869.

11) Pamela L. Spath, Margaret K. Mann, and Dawn R. Kerr, "Life Cycle Assessment of Coal-fired Power Production," National Renewable Energy Laboratory, Golden, Colorado, USA, (1999). doi:10.2172/12100.

12) D. Pudasainee, V. Kurian, and R. Gupta, "Coal: past, present, and future sustainable use," Future Energy (Third Edition), Elsevier, 21–48 (2020). doi:10.1016/B978-0-08-102886-5.00002-5.

13) R.A. Kruger, "Introduction to the utilization of coal combustion products," in: Coal Combustion Products (CCPs): Characteristics, Utilization and Beneficiation, Woodhead Publishing, (2017): 99–119. doi:10.1016/B978-0-08-100945-1.00004-6.

14) T.P. Adinugroho, U. Ayuningtyas, P. Anggraeni, H. Febriansyah, I.M.A.D. Susila, N.A. Sasongko, and N.T.E. Darmayanti, "Life cycle assessment of fly ash bottom ash in coal power plants: a review," IOP Conf Ser Earth Environ Sci, 1108 (1) 012035 (2022). doi:10.1088/1755-1315/1108/1/012035.

15) I. Dunmade, N. Madushele, P.A. Adedeji, and E.T. Akinlabi, "A streamlined life cycle assessment of a coal-fired power plant: the south african case study," Env Sci and Pollution R., 26 (18) 18484–18492 (2019). doi:10.1007/S11356-019-05227-6/FIGURES/9.

16) F. Agrela, M. Cabrera, M.M. Morales, M. Zamorano, and M. Alshaaer, "Biomass fly ash and biomass bottom ash," Woodhead Publishing, Elsevier, 2018: 23–58. doi:10.1016/B978-0-08-102480-5.00002-6.

17) S. Maschio, G. Tonello, L. Piani, and E. Furlani, "Fly and bottom ashes from biomass combustion as cement replacing components in mortars production: rheological behaviour of the pastes and materials compression strength," Chemosphere, 85 (4) 666–671 (2011). doi:10.1016/ j.chemosphere.2011.06.070.

18) V. Sahu, A.K. Misra, and V. Gayathri, "Fly ash in road construction," in: Handbook of Fly Ash, Elsevier, Department of Civil and Environmental Engineering, The NorthCap University, Gurugram, India, (2021): 657–680. doi:10.1016/B978-0-12-817686-3.00024-4.

19) S.K. Ghosh, and V. Kumar, "Circular economy and fly ash management," (2019), Springer Nature Singapore Pte Ltd. doi:10.1007/978-981-15-0014-5.

20) A.K. James, R.W. Thring, P.M. Rutherford, and S.S. Helle, "Characterization of biomass bottom ash from an industrial scale fixed-bed boiler by fractionation," Energy and Env. R., 3 (2) (2013). doi:10.5539/eer.v3n2p21.

21) R.C.E. Modolo, V.M. Ferreira, L.A. Tarelho, J.A. Labrincha, L. Senff, and L. Silva, "Mortar formulations with bottom ash from biomass combustion," Constr Build Mater, 45 275–281 (2013). doi: 10.1016/j.conbuildmat. 2013.03.093.

22) R. Moradi, A. Marto, A.S.A. Rashid, M.M. Moradi, A.A. Ganiyu, M.H. Abdullah, and S. Horpibulsuk, "Enhancement of soft soil behaviour by using floating bottom ash columns," KSCE J. Civ. Eng, 23 (6) 2453–2462 (2019). doi:10.1007/s12205-019-0617-x.

23) M.L.D. Jayaranjan, E.D. van Hullebusch, and A.P. Annachhatre, "Reuse options for coal fired power

plant bottom ash and fly ash," Rev Environ Sci Biotechnol, 13 (4) 467–486 (2014). doi:10.1007/S11157-014-9336-4/TABLES/6.

24) Z.T. Yao, X.S. Ji, P.K. Sarker, J.H. Tang, L.Q. Ge, M.S. Xia, and Y.Q. Xi, "A comprehensive review on the applications of coal fly ash," Earth Sci Rev, 141 105–121 (2015). doi:10.1016/J.EARSCIREV.2014.11.016.

25) H. Zhou, R. Bhattarai, Y. Li, B. Si, X. Dong, T. Wang, and Z. Yao, "Towards sustainable coal industry: turning coal bottom ash into wealth," Science of The Total Environment, 804 149985 (2022). doi:10.1016/J.SCITOTENV.2021.149985.

26) Electric Power Research Institute (EPRI), "Coal Ash: Characteristics, Management and Environmental Issues," Electric Power Research Institute (EPRI), Palo Alto, California, USA, (2009). http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=00000000000 1019022. (accessed June 26, 2024).

27) L. Wright, and J.M. Khatib, "Sustainability of desulphurised (fgd) waste in construction," Sustainability of Construction Materials, 683–715 (2016). doi:10.1016/B978-0-08-100370-1.00026-3.

28) E.O. Ezugbe, and S. Rathilal, "Membrane technologies in wastewater treatment: a review," Membranes (Basel), 10 (5) (2020). doi:10.3390/membranes10050089.

29) G. Crini, and E. Lichtfouse, "Advantages and disadvantages of techniques used for wastewater treatment," Environ Chem Lett, 17 (1) 145–155 (2019). doi:10.1007/s10311-018-0785-9.

30) Y. Masaki, "Characteristics of industrial wastewater discharged from industrialized provinces and specific industrial sectors in china based on the official statistical reports," *Evergreen*, 3(2) 59–67 (2016). doi:10.5109/1800873.

31) A. Berisha, and L. Osmanaj, "Kosovo scenario for mitigation of greenhouse gas emissions from municipal waste management," *Evergreen*, 8(3) 509–516 (2021). doi:10.5109/4491636.

32) R. Shrestha, S. Ban, S. Devkota, S. Sharma, R. Joshi, A.P. Tiwari, H.Y. Kim, and M.K. Joshi, "Technological trends in heavy metals removal from industrial wastewater: a review," J Environ Chem Eng, 9 (4) 105688 (2021). doi:1016/j.jece.2021.105688.

33) H. Lu, J. Wang, T. Wang, N. Wang, Y. Bao, and H. Hao, "Crystallization techniques in wastewater treatment: an overview of applications," Chemosphere, 173 474–484 (2017). doi:10.1016/j.chemosphere.2017.01.070.

34) Y. Lu, A. Tian, J. Zhang, Y. Tang, P. Shi, Q. Tang, and Y. Huang, "Physical and chemical properties, pretreatment, and recycling of municipal solid waste incineration fly ash and bottom ash for highway engineering: a literature review," Advances in Civil Eng, 2020 (1) (2020). doi:10.1155/2020/ 8886134.

35) J.H. Park, J.H. Eom, S.L. Lee, S.W. Hwang, S.H. Kim, S.W. Kang, J.J. Yun, J.S. Cho, Y.H. Lee, and D.C. Seo, "Exploration of the potential capacity of fly ash and bottom ash derived from wood pellet-based thermal power plant for heavy metal removal," J of Sci of The Total Env, 740 140205 (2020). doi:10.1016/J.SCITOTENV.2020.140205.

36) C.Y. Lin, and D.H. Yang, "Removal of pollutants from wastewater by coal bottom ash," Http://Dx.Doi.Org/10.1081/ESE-120013273, 37 (8) 1509–1522 (2007). doi:10.1081/ESE-120013273.

37) A. Labidi, H. Ren, A. Sial, H. Wang, E. Lichtfouse, and C. Wang, "Coal ash for removing toxic metals and phenolic contaminants from wastewater: a brief review," Crit Rev Environ Sci Technol, 53 (23) 2006–2029 (2023). doi:10.1080/10643389.2023.2206781.

38) UNIDO, "Role of standards - A guide for small and medium-sized enterprises," UNIDO, Vienna, (2006). https://www.unido.org/role-standards-guide-small-and-medium-sized-enterprises. (accessed June 26, 2024).

39) D.A. Susanto, E. Kristiningrum, and T.P. Adinugroho, "Designing a framework for standardization and testing requirements for the solar-powered water pump system," IOP Conf Ser Earth Environ Sci, 1133 (1) 012071 (2023). doi:10.1088/1755-1315/1133/1/012071.

40) D.A. Susanto, F. Isharyadi, and M. Ritonga, "Economic benefits of implementing standards in small and medium enterprises using ISO methodology," Jurnal Standardisasi, 19 (1) 25–37 (2017). doi:10.31153/js.v19i1.411.

41) A.T. Setyoko, E. Kristiningrum, D.A. Susanto, A. Achmadi, and M. Ayundyahrini, "Economic benefits of standard in SME laundry equipment producer using ISO methodology," AIP Conf. Proc. 2664 040003 (2022). doi:10.1063/5.0108798.

42) P.D. Denton, and M.K. Maatgi, "The development of a work environment framework for iso 9000 standard success," Int J of Quality & Reliability Mng, 33 (2) 231–245 (2016). doi:10.1108/IJQRM-12-2013-0196.

43) P. Chatzoglou, D. Chatzoudes, and N. Kipraios, "The impact of iso 9000 certification on firms' financial performance," Int J of Operations & Production Mng, 35 (1) 145–174 (2015). doi:10.1108/IJOPM-07-2012-0387.

44) E. Kristiningrum, M. Ayundyahrini, D.A. Susanto, A.T. Setyoko, R.H. Kresiani, and N. Suparmanto, "Quantifying the economic benefit of standard on auto-electric stove for batik small medium enterprises in indonesia," Heliyon, 7 (6) e07299 (2021). doi:10.1016/j.heliyon.2021.e07299.

45) E. Psomas, and A. Pantouvakis, "ISO 9001 overall performance dimensions: an exploratory study," The

TQM J, 27 (5) 519–531 (2015). doi:10.1108/TQM-04-2014-0037.

46) A.P. Kakouris, and E. Sfakianaki, "Impacts of iso 9000 on greek smes business performance," Int J of Quality & Reliability Mng, 35 (10) 2248–2271 (2018). doi:10.1108/IJQRM-10-2017-0204.

47) S. Jin, Z. Zhao, S. Jiang, J. Sun, H. Pan, and L. Jiang, "Comparison and summary of relevant standards for comprehensive utilization of fly ash at home and abroad," in: IOP Conf Ser Earth Environ Sci, (2021). doi:10.1088/1755-1315/621/1/012006.

48) A.S. for Testing, and Materials, "ASTM c 618-03 standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete," (n.d.). doi:10.1520/C0618-23E01.

49) J.I.S.C. (JISC), "JIS a 6201: 2015 fly ash for concrete," (n.d.). https://jis.eomec.com/jisa62012015#toc1.

50) C.S.A. Committee, "GB/t 1596-2017 fly ash used for cement and concrete," (n.d.). https://www.chinesestandard.net/PDF.aspx/GBT1596-2017. https://www.chinesestandard.net/PDF.aspx/GBT1596-2017. (accessed June 26, 2024).

51) E.C. for Standardization, "EN 450-1:2012 fly ash for concrete - part 1: definition, specifications and conformity criteria," (n.d.). https://standards.iteh.ai/catalog/standards/cen/cc9c0d2c-6d67-4290-82ea-e5e99eb8abf0/en-450-1-2012. (accessed June 26, 2024).

52) B.S.N. (BSN), "SNI 2460:2014 (astm c 618-08a, idt) - specifications of raw or calcined natural pozzolan and coal fly ash for use in concrete," (2014). https://akses-sni.bsn.go.id/viewsni/baca/5752. (accessed June 26, 2024).

53) M. Ayello, and Y. Lopes, "Interoperability based on iec 61850 standard: systematic literature review, certification method proposal, and case study," Electric Power Syst R, 220 109355 (2023). doi:10.1016/j.epsr.2023.109355.

54) M. de Freitas Junior, M. Fantinato, and V. Sun, "Improvements to the function point analysis method: a systematic literature review," IEEE Trans Eng Manag, 62 (4) 495–506 (2015). doi:10.1109/TEM.2015.2453354.

55) S.S. Alterary, and N.H. Marei, "Fly ash properties, characterization, and applications: a review," J King Saud Univ Sci, 33 (6) 101536 (2021). doi:10.1016/j.jksus.2021.101536.

56) P. Witherell, S. Rachuri, A. Narayanan, and J.H. Lee, "FACTS: a framework for analysis, comparison, and testing of standards (nistir 7935)," 33 (2013). doi:10.6028/ NIST.IR.7935.

57) N. Aristyawati, F. Fahma, W. Sutopo, A. Purwanto, M. Nizam, B.B. Louhenapessy, and A.B. Mulyono, "Designing framework for standardization and testing requirements for the secondary battery a case study of lithium-ion battery module in electric vehicle application," in: 2016 2nd International Conference of Industrial, Mechanical, Electrical, and Chemical Engineering (ICIMECE), IEEE, 2016: pp. 207–212. doi:10.1109/ICIMECE.2016.7910459.

58) W. Sutopo, B. Rahmawatie, F. Fahma, M. Nizam, A. Purwanto, B.B. Louhenapessy, and E. Abdul Kadir, "A technical review of bms performance standard for electric vehicle applications in indonesia," TELKOMNIKA (Telecommunication Computing Electronics and Control), 16 (2) 544 (2018). doi:10.12928/telkomnika.v16i2.7930.

59) R.A. Pratiwi, F. Fahma, W. Sutopo, E. Pujiyanto, Suprapto, and M. Ayundyahrini, "Designing parameter for developing standard of manual wheelchair," Int J of Applied Sci and Eng, 15 (2) 127–134 (2018). doi:10.6703/IJASE.201810_15(2).127.

60) I.O. Sanya, and E.M. Shehab, "A framework for developing engineering design ontologies within the aerospace industry," Int J Prod Res, 53 (8) 2383–2409 (2015). doi:10.1080/00207543.2014.965352.

61) M. Rafieizonooz, E. Khankhaje, and S. Rezania, "Assessment of environmental and chemical properties of coal ashes including fly ash and bottom ash, and coal ash concrete," J of Building Eng, 49 104040 (2022). doi:10.1016/ j.jobe.2022.104040.

62) K.M. Zierold, and C. Odoh, "A review on fly ash from coal-fired power plants: chemical composition, regulations, and health evidence," Rev Environ Health, 35 (4) 401–418 (2020). doi:10.1515/reveh-2019-0039.

63) E. Loginova, D.S. Volkov, P.M.F. van de Wouw, M.V.A. Florea, and H.J.H. Brouwers, "Detailed characterization of particle size fractions of municipal solid waste incineration bottom ash," J Clean Prod, 207 866–874 (2019). doi:10.1016/ j.jclepro.2018.10.022.

64) R.-G. Kim, D. Li, and C.-H. Jeon, "Experimental investigation of ignition behavior for coal rank using a flat flame burner at a high heating rate," Exp Therm Fluid Sci, 54 212–218 (2014). doi:10.1016/j.expthermflusci.2013.12.017.

65) S.A. Mohammed, S. Koting, H.Y.B. Katman, A.M. Babalghaith, M.F. Abdul Patah, M.R. Ibrahim, and M.R. Karim, "A review of the utilization of coal bottom ash (cba) in the construction industry," Sustainability, 13 (14) 8031 (2021). doi:10.3390/su13148031.

66) S. Matsumoto, S. Ogata, H. Shimada, T. Sasaoka, G.J. Kusuma, and R.S. Gautama, "Application of coal ash to postmine land for prevention of soil erosion in coal mine in indonesia: utilization of fly ash and bottom ash," Adv in Materials Sci and Eng, 2016 1–8 (2016). doi:10.1155/2016/8386598.

67) F.-Y. Chang, and M.-Y. Wey, "Comparison of the characteristics of bottom and fly ashes generated from various incineration processes," J Hazard Mater, 138 (3) 594–603 (2006). doi:10.1016/ j.jhazmat.2006.05.099.

68) X. Dou, F. Ren, M.Q. Nguyen, A. Ahamed, K. Yin, W.P. Chan, and V.W.-C. Chang, "Review of mswi bottom ash utilization from perspectives of collective characterization, treatment and existing application," J of Renewable and Sustainable Energy Rev, 79 24–38 (2017). doi:10.1016/ j.rser.2017.05.044.

69) N.B. Singh, A. Agarwal, A. De, and P. Singh, "Coal fly ash: an emerging material for water remediation," Int J Coal Sci Technol, 9 (1) 44 (2022). doi:10.1007/s40789-022-00512-1.

70) V.C. Srivastava, I.D. Mall, and I.M. Mishra, "Modelling individual and competitive adsorption of cadmium(ii) and zinc(ii) metal ions from aqueous solution onto bagasse fly ash," Sep Sci Technol, 41 (12) 2685–2710 (2006). doi:10.1080/ 01496390600725687.

71) L. Taoufiq, A. Laamyem, A. Boukhair, E. Essediqi, M. Monkade, and A. Zrabda, "Radiological assessment of wastewater treatment processes based on the use of coal ashes as a filters," J Radiat Res Appl Sci, 11 (3) 217–224 (2018). doi:10.1016/ J.JRRAS.2018.01.006.

72) V. Gadore, and Md. Ahmaruzzaman, "Tailored fly ash materials: a recent progress of their properties and applications for remediation of organic and inorganic contaminants from water," J of Water Process Eng, 41 101910 (2021). doi:10.1016/j.jwpe.2020.101910.

73) F. Mushtaq, M. Zahid, I.A. Bhatti, S. Nasir, and T. Hussain, "Possible applications of coal fly ash in wastewater treatment," J Environ Manage, 240 27–46 (2019). doi:10.1016/j.jenvman. 2019.03.054.

74) S. Buzukashvili, R. Sommerville, W. Hu, O. Brooks, O. Kökkılıç, P. Ouzilleau, N.A. Rowson, and K.E. Waters, "Zeolite synthesis from coal fly ash and its application to heavy metals remediation from water contaminated with pb, cu, zn and ni ions," Miner Eng, 209 (2024). doi:10.1016/j.mineng.2024.108619.

75) L. Xing, J. Luo, H. Jiang, X. Zhang, M. Rao, and G. Li, "Using solid waste to treat wastewater: preparation of flowerlike calcium silicate hydrate from coal fly ash for cadmium removal," Sep Purif Technol, 348 (2024). doi:10.1016/j.seppur. 2024.127690.

76) S. Zhang, L. Yu, Y. Zhang, Q. Liu, J. Xia, J. Tian, H. Zhang, and X. Lu, "Removal of anionic dyes from wastewater using fly ash based adsorbent," Desalination Water Treat, 317 1-6 (2024). doi:10.1016/ j.dwt.2024.100007.

77) A. Alghifary, and Y.I. Sihombing, "Permeable reactive barrier as a sustainable and environmentally friendly innovation for acid mine water remediation in indonesia," Jurnal Himasapta, 6 (3) 159–170 (2021). doi:10.20527/jhs.v6i3.4680.

78) T. Lekgoba, F. Ntuli, and T. Falayi, "Application of coal fly ash for treatment of wastewater containing a binary mixture of copper and nickel," J of Water Process Eng, 40 (2021). doi:10.1016/j.jwpe.2020.101822.

79) G. El mouhri, M. Merzouki, R. Kachkoul, H. Belhassan, Y. Miyah, H. Amakdouf, R. Elmountassir, and A. Lahrichi, "Fixed-bed adsorption of tannery wastewater pollutants using bottom ash: an optimized process," J of Surfaces and Interfaces, 22 100868 (2021). doi:10.1016/j.surfin.2020.100868.

80) C.Y. Lin, P.H. Hesu, and D.H. Yang, "Removal of hydrogen sulfide gas and landfill leachate treatment using coal bottom ash," J Air Waste Manag Assoc, 51 (6) 939–945 (2001). doi:10.1080/10473289. 2001.10464317.

81) K.S. Hashim, H.M. Ewadh, A.A. Muhsin, S.L. Zubaidi, P. Kot, M. Muradov, M. Aljefery, and R. Al-Khaddar, "Phosphate removal from water using bottom ash: adsorption performance, coexisting anions and modelling studies," Water Sci and Tech, 83 (1) 77–89 (2021). doi:10.2166/wst.2020.561.

82) M.F. Chong, K.P. Lee, H.J. Chieng, and I.I. Syazwani Binti Ramli, "Removal of boron from ceramic industry wastewater by adsorption-flocculation mechanism using palm oil mill boiler (pomb) bottom ash and polymer," Water Res, 43 (13) 3326–3334 (2009). doi:10.1016/j.watres.2009. 04.044.

83) T. Benzaoui, A. Selatnia, and D. Djabali, "Adsorption of copper (ii) ions from aqueous solution using bottom ash of expired drugs incineration," Adsorption Sci & Tech, 36 (1–2) 114–129 (2017). doi:10.1177/ 0263617416685099.

84) M. Zbair, A. El Hadrami, A. Bellarbi, M. Monkade, A. Zradba, and R. Brahmi, "Herbicide diuron removal from aqueous solution by bottom ash: kinetics, isotherm, and thermodynamic adsorption studies," J Environ Chem Eng, 8 (2) 103667 (2020). doi:10.1016/j.jece.2020.103667.

85) H. Wang, X. Wang, Z. Xu, and M. Zhang, "Synthetic zeolite from coal bottom ash and its application in cadmium and nickel removal from acidic wastewater," Desalination Water Treat, 57 (54) 26089–26100 (2016). doi:10.1080/19443994. 2016.1160438.

86) I. Susanto, R.R. Irawan, Y. Ronny, and G. Gunawan, "Coal ash waste utilization for environmentally friendly road pavement materials," IOP Conf Ser Earth Environ Sci, 448 (1) 012116 (2020). doi:10.1088/1755-1315/448/1/012116.

87) C. He, J. Bai, A. Ilyushechkin, H. Zhao, L. Kong, H. Li, Z. Bai, Z. Guo, and W. Li, "Effect of chemical composition on the fusion behaviour of synthetic high-iron coal ash," Fuel, 253 1465–1472 (2019). doi:10.1016/j.fuel.2019.05.135.

88) W. Shi, X. Dai, J. Bai, L. Kong, J. Xu, X. Li, Z. Bai, and W. Li, "A new method of estimating the liquidus temperature of coal ash slag using ash composition,"

Chem Eng Sci, 175 278–285 (2018). doi:10.1016/j.ces.2017.10.002.

89) N.K. Mahale, S.D. Patil, D.B. Sarode, and S.B. Attarde, “Effect of fly ash as an admixture in agriculture and study of heavy metal accumulation in wheat (triticum aestivum), mung bean (vigna radiata) and urad beans (vigna mungo),” Pol. J. Environ. Stud., 21 (6) 1713–1719 (2012). http://www.pjoes.com/pdf-88921-22780?filename=22780.pdf.

90) D.-S. Lee, S.-S. Lim, H.-J. Park, H.I. Yang, S.-I. Park, J.-H. Kwak, and W.-J. Choi, “Fly ash and zeolite decrease metal uptake but do not improve rice growth in paddy soils contaminated with cu and zn,” Environ Int, 129 551–564 (2019). doi:10.1016/j.envint.2019.04.032.

91) S. Jala, and D. Goyal, “Fly ash as a soil ameliorant for improving crop production—a review,” Bioresour Technol, 97 (9) 1136–1147 (2006). doi:10.1016/J.BIORTECH.2004.09.004.

92) R.Y. Agustini, I. Iskandar, S. Sudarsono, J. Jaswadi, and G. Wahdaniyah, “Utilization of coal bottom ash and cattle manure as soil ameliorant on acid soil and its effect on heavy metal content in mustard (brassica juncea),” Journal of Tropical Soils, 22 (2) 87–95 (2017). doi:10.5400/jts.2017.v22i2.87-95.

93) N. Trung Phan, T. Sengsingkham, P. Tiyayon, and K. Maneeintr, “Utilization of bottom ash for degraded soil improvement for sustainable technology,” IOP Conf Ser Earth Environ Sci, 268 (1) 012043 (2019). doi:10.1088/1755-1315/268/1/012043.

94) L. Han, J. Wang, Z. Liu, Y. Zhang, Y. Jin, J. Li, and D. Wang, “Synthesis of fly ash-based self-supported zeolites foam geopolymer via saturated steam treatment,” J Hazard Mater, 393 (January) 122468 (2020). doi:10.1016/j.jhazmat.2020.122468.

95) Z. Zhang, J. Wang, L. Liu, J. Ma, and B. Shen, “Preparation of additive-free glass-ceramics from msw incineration bottom ash and coal fly ash,” Constr Build Mater, 254 119345 (2020). doi:10.1016/j.conbuildmat.2020.119345.

96) K. Namkane, W. Naksata, S. Thiansem, P. Sooksamiti, and O. Arqueropanyo, “Utilization of coal bottom ash as raw material for production of ceramic floor tiles,” Environ Earth Sci, 75 (5) 386 (2016). doi:10.1007/s12665-016-5279-0.

97) H. Nollet, M. Roels, P. Lutgen, P. Van Der Meeren, and W. Verstraete, “Removal of pcbs from wastewater using fly ash,” Chemosphere, 53 (6) 655–665 (2003). doi:10.1016/S0045-6535(03)00517-4.

98) M. Visa, L. Isac, and A. Duta, “Fly ash adsorbents for multi-cation wastewater treatment,” Appl Surf Sci, 258 (17) 6345–6352 (2012). doi:10.1016/j.apsusc.2012.03.035.

99) M. Attari, S.S. Bukhari, H. Kazemian, and S. Rohani, “A low-cost adsorbent from coal fly ash for mercury removal from industrial wastewater,” J Environ Chem Eng, 5 (1) 391–399 (2017). doi:10.1016/j.jece.2016.12.014.

100) E.E. Chang, S.Y. Pan, L. Yang, Y.H. Chen, H. Kim, and P.C. Chiang, “Accelerated carbonation using municipal solid waste incinerator bottom ash and cold-rolling wastewater: performance evaluation and reaction kinetics,” Waste Mng, 43 283–292 (2015). doi:10.1016/j.wasman.2015.05.001.

101) F. Goembira, R. Putri, M. Ulfah, R. Yuliarningsih, M. Andrifar, and R. Aziz, “Evaluation of biodiesel catalysts derived from coal-fired teluk sirih power plant fly ash and bottom ash,” AIP Conf Proc, 2741 (1) 050012 (2023). doi:10.1063/5.0129148.

102) D. Längauer, V. Čablík, S. Hredzák, A. Zubrik, M. Matik, and Z. Danková, “Preparation of synthetic zeolites from coal fly ash by hydrothermal synthesis,” Materials, 14 (5) 1267 (2021). doi:10.3390/ma14051267.

103) V.K. Yadav, R. Suriyaprabha, G.K. Inwati, N. Gupta, B. Singh, C. Lal, P. Kumar, M. Godha, and H. Kalasariya, “A noble and economical method for the synthesis of low cost zeolites from coal fly ash waste,” Adv in Material and Processing Tech, 8 (sup2) 301–319 (2022). doi:10.1080/2374068X.2021.1927640.

104) C. Belviso, “State-of-the-art applications of fly ash from coal and biomass: a focus on zeolite synthesis processes and issues,” Prog Energy Combust Sci, 65 109–135 (2018). doi:10.1016/ j.pecs.2017.10.004.

105) K. Shaila, D. Nisha, P. Pralhad, and P. Deepa, “Zeolite Synthesis Strategies from Coal Fly Ash: A Comprehensive Review of Literature,” Int. Res. J. Environment Sci, 4(3), 93-99 (2015) http://www.isca.me/IJENS/Archive/v4/i3/13.ISCA-IRJEvS-2015-004.pdf.

106) A. Malviya, D.K. Jaspal, and S. Khamparia, “Kinetics studies on the adsorption of methyl orange and metanil yellow onto bottom ash: a comparative account,” Water Sci and Tech, 80 (10) 1844–1850 (2019). doi:10.2166/wst.2019.435.

107) L. Zhu, J. Ji, S. Wang, C. Xu, K. Yang, and M. Xu, “Removal of pb(ii) from wastewater using al2o3-naa zeolite composite hollow fiber membranes synthesized from solid waste coal fly ash,” Chemosphere, 206 278–284 (2018). doi:10.1016/j.chemosphere.2018.05.001.

108) P. Suraneni, L. Burris, C.R. Shearer, and R.D. Hooton, “ASTM c618 fly ash specification: comparison with other specifications, shortcomings, and solutions,” ACI Mater J, 118 (1) 157–167 (2021). doi:10.14359/51725994.

109) Y. Hu, L. Zhao, Y. Zhu, B. Zhang, G. Hu, B. Xu, C. He, and F. Di Maio, “The fate of heavy metals and salts during the wet treatment of municipal solid waste incineration bottom ash,” Waste Mng, 121 33–41 (2021). doi:10.1016/j.wasman.2020.11.049.

110) D. Bansal, G. Gupta, G.V. Ramana, and M. Datta, “Optimizing msw incineration bottom ash reuse: a

study on treated wastewater washing and leaching control," Waste Mng, 182 164–174 (2024). doi:10.1016/j.wasman.2024.04.035.

111) M.U.K. Khobragade, and A. Pal, "Batch and continuous fixed-bed column adsorption for the removal of ni (ii) from aqueous solutions using surfactant-treated alumina," Recent Patents on Eng, 10 (1) 36–50 (2015). doi:10.2174/1872212110666151218204647.

112) N. Ranjbar, and C. Kuenzel, "Cenospheres: a review," Fuel, 207 1–12 (2017). doi:10.1016/J.FUEL.2017.06.059.

113) A. Danish, and M.A. Mosaberpanah, "Formation mechanism and applications of cenospheres: a review," J Mater Sci, 55 (11) 4539–4557 (2020). doi:10.1007/s10853-019-04341-7.

114) P. Chen, X. Shen, S. Li, and J. Wang, "Effect of wastewater generated from fluoroacid etching of cenospheres on the performance of alkali-activated slag," Constr Build Mater, 403 133163 (2023). doi:10.1016/j.conbuildmat.2023.133163.

115) M. Priya, J. Jeyanthi, and G. Thiruvenkatamani, "Recycling of industrial waste material of fly ash cenosphere for the treatment of car wash water effluent," J Mater Cycles Waste Manag, 24 (1) 321–332 (2022). doi:10.1007/s10163-021-01324-2.

116) H.T.B.M. Petrus, M. Olvianas, W. Suprapta, F.A. Setiawan, A. Prasetya, Sutijan, and F. Anggara, "Cenospheres characterization from indonesian coal-fired power plant fly ash and their potential utilization," J Environ Chem Eng, 8 (5) (2020). doi:10.1016/j.jece.2020.104116.

117) J. Santhosh Kumar, R. Beura, and P. Thangadurai, "Role of Metal and Metal Oxides for the Removal of Water Pollutants," in: S. Rajendran, Mu. Naushad, D.-V.N. Vo, E. Lichtfouse (Eds.), Inorganic Materials for Energy, Medicine and Environmental Remediation, Springer International Publishing, Cham, (2022). 99–130. doi:10.1007/978-3-030-79899-4_5.

118) S.D. Shirsat, R.S. Mane, J. Bauer, and N.D. Thorat, "Metal oxide nanocomposites in water and wastewater treatment," Advances in Metal Oxides and Their Composites for Emerging Applications, 479–522 (2022). doi:10.1016/B978-0-323-85705-5.00003-8.

119) A. Assi, F. Bilo, S. Federici, A. Zacco, L.E. Depero, and E. Bontempi, "Bottom ash derived from municipal solid waste and sewage sludge co-incineration: first results about characterization and reuse," Waste Mng, 116 147–156 (2020). doi:10.1016/j.wasman.2020.07.031.

120) N.T. Lam, "Assessment of the compressive strength and strength activity index of cement incorporating fly ash," in: IOP Conf Ser Mater Sci Eng, (2020). doi:10.1088/1757-899X/869/3/032052.

121) S.B. H, "Study of the unburned carbon content of ash and propose one new technology separated the ash and unburned carbon discharged by the coal-fire thermal power plants in vietnam," IJISET - Int J of Innovative Sci, Eng & Tech, 6 (5) 296–300 (2019). https://ijiset.com/vol6/v6s5/IJISET_V6_I5_43.pdf

122) S. Wang, and H. Wu, "Environmental-benign utilisation of fly ash as low-cost adsorbents," J Hazard Mater, 136 (3) 482–501 (2006). doi:10.1016/j.jhazmat.2006.01.067.

123) M. Ahmaruzzaman, "Role of fly ash in the removal of organic pollutants from wastewater," Energy & Fuels, 23 (3) 1494–1511 (2009). doi:10.1021/ef8002697.

124) M. Shen, T. Hu, W. Huang, B. Song, M. Qin, H. Yi, G. Zeng, and Y. Zhang, "Can incineration completely eliminate plastic wastes? an investigation of microplastics and heavy metals in the bottom ash and fly ash from an incineration plant," Sci of The Total Env, 779 146528 (2021). doi:10.1016/j.scitotenv.2021.146528.

125) M. Thevaraja, "Copula Theory and Regression Analysis," Minnesota State University Mankato, (2018). https://cornerstone.lib.mnsu.edu/cgi/viewcontent.cgi?article=1801&context=etds.

126) J.-H. Shih, Y. Konno, Y.-T. Chang, and T. Emura, "Copula-based estimation methods for a common mean vector for bivariate meta-analyses," Symmetry (Basel), 14 (2) 186 (2022). doi:10.3390/sym14020186.

127) R. de F.S.M. Russo, and R. Camanho, "Criteria in ahp: a systematic review of literature," Procedia Comput Sci, 55 1123–1132 (2015). doi:10.1016/j.procs.2015.07.081.

128) Y. Liu, C.M. Eckert, and C. Earl, "A review of fuzzy ahp methods for decision-making with subjective judgements," Expert Syst Appl, 161 113738 (2020). doi:10.1016/j.eswa.2020.113738.

129) M.R. Asadabadi, E. Chang, and M. Saberi, "Are mcdm methods useful? a critical review of analytic hierarchy process (ahp) and analytic network process (anp)," Cogent Eng, 6 (1) (2019). doi:10.1080/23311916.2019.1623153.

130) E. Kristriningrum, D.A. Susanto, and T.P. Adinugroho, "Determination of priority SNI-certified-products with AHP approach – A case study on food and beverage sector," in: (2022): p. 040008. doi:10.1063/5.0108211.

131) F. Isharyadi, and E. Kristiningrum, "Profile of system and product certification as quality infrastructure in indonesia," Open Eng, 11 (1) 556–569 (2021). doi:10.1515/eng-2021-0054.

132) D.A. Susanto, "Implementation of standards in international trade: benefit or barrier? a case study from indonesia," *Evergreen*, 9(3) 619–628 (2022). doi:10.5109/4842518.