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Assessment of the Solid Waste Disposal from Yatağan Power Plant in Türkiye

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Abstract

The aims of this study were characterization of fly ash samples through mineralogical and chemical composition, determination of heavy concentrations for better environmental sustainability. Coal fly ash, by-product of the combustion of coal, contains heavy metals like Cd, Cr, Cu, Fe, Mn, Ni, Sr, and Zn. The disposal of coal fly ash to the landfill may harm the environment due to the toxicity of heavy metals entering into water or groundwater.

The laboratory experimental results indicate that the fly ash contains hazardous metals such as Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sr, and Zn with a concentration higher than the permissible concentration of waste disposal. Mineralogical analysis showed the presence of quartz ($SiO2$), albite ($NaAlSi_3O_8$), anhydrite ($CaSO4$), gehlenite ($Ca2Al[AlSiO_7]$), lime (CaO), and hematite (Fe_2O_3), with quartz being the principal mineral. The fine particle size and alkaline pH of the fly ash enhance the leaching potential of heavy metals when exposed to water and atmospheric conditions, which may contribute to soil and groundwater contamination.

Keywords: Hazardous Metals; Characterization; Environmental Contamination; Fly Ash.

1. Introduction

Coal fly ash is a product obtained by burning coal in thermal power plants. Generally, these plants consume millions of tons of coal, and generate large quantities of fly ash every year. In Turkey, the Yatagan power plant utilizes 5.4 million tons of coal and discharge 1.8 million tons every year (Baba et al., 2003). However, the large production of fly ashes during incineration and thermal plant causes several negative environmental effects (Gutiérrez et al., 1997; Li et al., 2025; Ma et al., 2025; Querol et al., 2000). Previous studies have demonstrated that coal fly ash contains several amounts of major element compounds like oxides, hydroxides, and sulfates of iron and calcium, as well as the presence of heavy metals such as: As, B, Cd, Co, Cr, Fe, Mn, Ni, Pb, Sb, Se, Sr, Ti, and Zn (Bhattacharyya et al., 2009; Jankowski et al., 2006).

The term "heavy metals" as defined by (Thornton, 1995) are metals that have a density greater than 6 g cm^{-3} (i.e., Fe, Cu, Pb, Zn, Sn, Ni, Co, Mo, W, Hg, Cd, etc.). These metals are also toxic and are released into the soil and water through different sources. The two main sources of heavy metals are natural and anthropogenic (Liu et al., 2018; Masindi & Muedi, 2018; Sindern et al., 2016). The natural origin of the latter is the consequence of the geogenic process which includes the dissolution of metalliferous rock and igneous eruption (Garbarino et al., 1995; Ali et al., 2019). Whereas the anthropogenic sources were caused by agriculture activity, industrials and mining activities such as cosmetics,

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paints and pigments, varnish, mining, mineral processing plant and metallurgical extraction (Chaney, 1989; Aykol et al., 2003; Yalcin & Ilhan, 2008; Mahar et al., 2016).

Both origins of heavy metals contaminate the environment and represent a danger to human health (Chapiou et al., 2022). For example, the environmental contamination from the mobility of Pb may result in important adverse consequences such as loss of ecosystems, human and animal health problems and economical losses (Bulut, 2006; Pruvot et al., 2010).

The interaction of heavy metals with water in ponds or landfills enhances by far their mobilities from fly ash surface (Iyer; 2002; Świetlik et al; 2012). Furthermore, their mobility of heavy metals is affected by their distributions and forms in coal combustion by-products (Bayat, 2002; Świetlik et al., 2012).

Regarding iron pollution, iron (II) oxidizes with the pyrite (FeS_2) ion to produce acid mining drainage (AMD) and polluted surface and underground water. The high-level concentration of iron in drinking water induces human health issues such as staining fixtures and laundry and causes an astringent taste (Sarkar & Shekhar, 2018). Therefore, this study aims to investigate the impact of disposal of fly ash into the environment through the physicochemical tests.

2. Materials and Methods

2.1. Study Area

Yatağan thermal power plant is located at 30 km northwest of Mugla City; the west part of Aegean Region-Turkey (**Figure 1**). This thermal plant consumes low quality lignite, mined by TKI (Turkish Coal Enterprises) in the Eskihisar, Tınaz and Bagyaka Basins, and used after crushing in the plant.

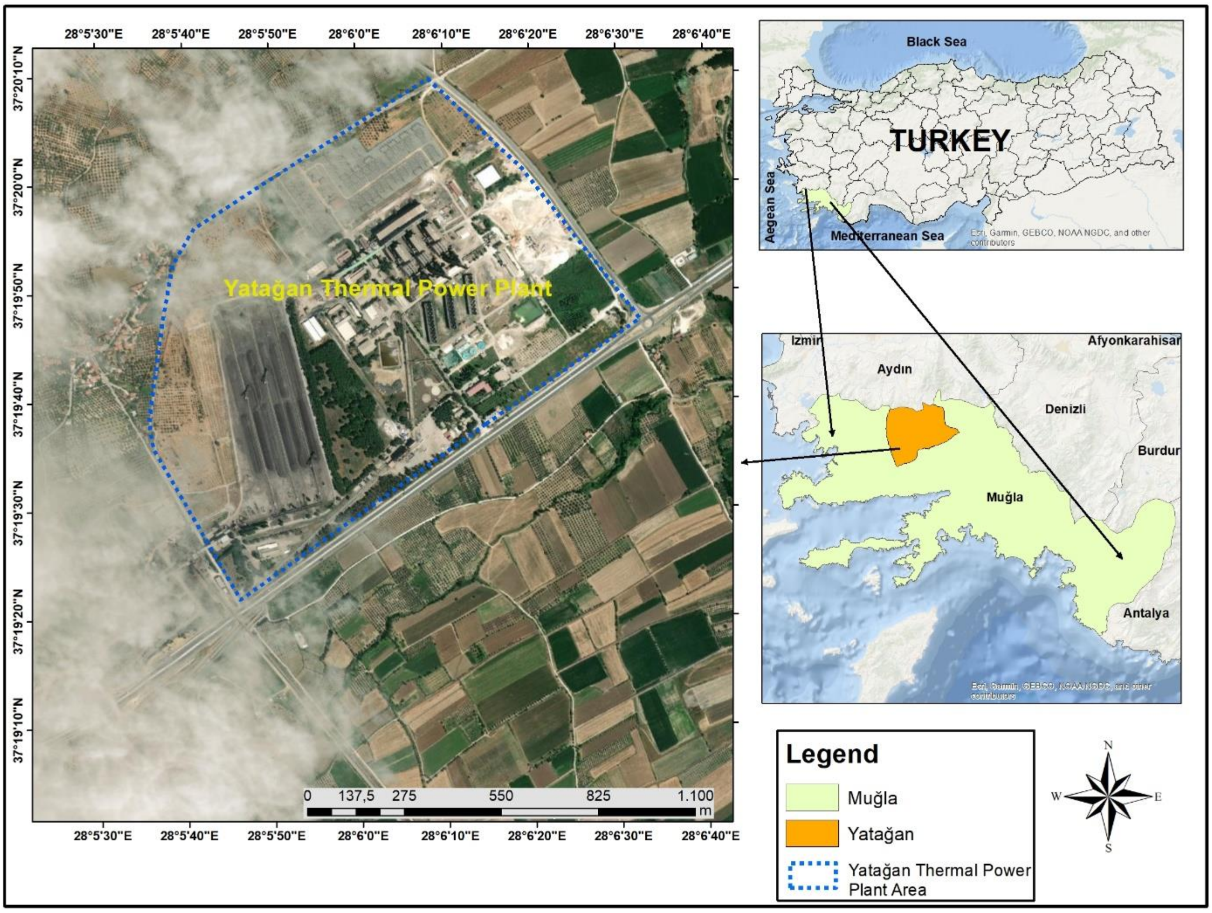

Figure 1 Map of Yatağan power plant location

The fly ash sample from was obtained from theYatağan power plant, then prepared by the mechanical preparation such as crushing, grinding, and collected the representative sample. As sous as the sample came to the laboratory, a determination of water content was realized. To achieve that 20 of fly ash sample in a dry oven at 105°C for 24 h. Afterward, the dry samples were cooled in a desiccator and the content was weighed with the precision balance (model Radwag). The moisture value was obtained by computing the difference between the initial weight (wet) and the dry weight sample (Chapiou, 2022).

The obtained representative sample was tested through the physicochemical method. This method includes the determination of pH, surface area, size distribution, mineralogical composition, chemical compounds and heavy metal concentrations.

2.2. X-ray and XRF analyses

The analysis of XRD is considered the most concise and useful technique for identifying the mineral composition in soil or powder sample (Bish, 1994; Holder & Schaak, 2019). In our study, the determination mineral component of fly ash sample was performed by using X-ray diffractometer Rigaku Miniflex (D/Max 600, Cu Kα radiation: 1.54059 Å, 33 KV, 15 m Å).

The fly ash sample (particle size below 100µm) were analyzed by using XRF spectrometer (Model: Spectro iQ II, Kleve, Germany). The characteristics of spectrometer are the detector of silicon drift 145eV 10000 pulses for resolution and utilized X-ray tube (25-50 kV) with a highly oriented pyrolytic graphite (HOPG) crystal for the analysis.

2.3. Metal dissolution test and analyses

The metal dissolution experiment by CEM microwave (Model: Mars 6240/50, power: 400-1800) digestion system (**Figure 2**). This device is currently the most popular digestion system for acid leaching of heavy metal from solid and can heat up to forty samples in one run. To perform the leaching test, 10 ml HNO_3, 5ml HF and 5ml of de-ionized water (2:1.1 ratio) were added to four TFM vessel liners containing 0.2g of fly ash sample. Thus, the vessels are closed with the standard cover and are loaded in the CEM microwave. Before running the digestion, the temperature of CEM microwave is adjusted to 200°C within 15 minutes for ramping, and the same temperature (200°C) is kept at10 minutes, and 50°C in 15 minutes for cooling. After cooling, the leachate solution was put into a volumetric flask and filled to 250 ml volume using de-ionized water. The final step is the determination of heavy metal concentration in the leachate solution by inductively coupled plasma (ICP, model: Varian 710-ES ICP-OES). As presented in Table 1, quality assurance and quality control (QA/QC) are performed following the experimental design described by (**Tasgetiren, 2014**).

Figure 2 Image of CEM Microwave digestion system. (a) Vessels loading, (b) At the starting of microwave operation (Chapiou, 2022)

Table 1 Limit of detection (LOD) and Limit of quantifications

Standard Metals Concentrations (mg/L)	Measured Concentrations (mg/L)										Means	SD(±)	LOD	LOQ
Cd	2.04	2.06	2.03	1.98	2.04	2.04	2.01	2.02	2.02	1.97	2.0202	0.0279	0.0836	0.2786
Co	5.02	5.05	5.05	4.95	5.08	5.07	4.97	5.04	4.99	4.98	5.0210	0.0451	0.1354	0.4514
Cr	4.97	5.06	4.98	4.96	5.01	5.04	4.98	5.03	4.96	4.99	4.9973	0.0353	0.1060	0.3532
Cu	5.05	5.01	5.07	4.96	5.08	5.06	5.02	5.07	5.01	4.98	5.0303	0.0397	0.1191	0.3971
Fe	5.07	5.03	5.04	4.98	5.06	5.07	4.97	5.03	4.99	4.97	5.0218	0.0390	0.1171	0.3904
Mn	5.06	5.06	4.98	4.98	5.04	5.03	5.02	5.03	5.02	5.03	5.0244	0.0285	0.0855	0.2850
Ni	5.00	5.08	5.02	4.97	5.04	5.00	4.94	5.02	4.97	4.96	4.9986	0.0417	0.1252	0.4173
Pb	4.98	5.03	4.99	4.99	5.04	5.01	4.98	5.05	4.95	4.97	4.9982	0.0321	0.0964	0.3212
Sr	4.96	4.95	5.02	4.99	4.97	5.09	5.03	4.97	5.04	5.08	5.0084	0.0515	0.1546	0.5154
Zn	5.05	5.01	5.02	4.98	5.02	5.03	5.02	5.04	5.01	5.03	5.0208	0.0192	0.0576	0.1919

3. Results and Discussions

3.1. Physical Properties of Fly Ash

The particle size distributions of the coal fly ash samples were plotted in Figure 3. As seen, more than 80 % of Yatağan particles are below 82 µm, and more than 30% of particles are under 17 µm. The median particle diameter is approximately 30 µm. This fine granulometry is typical of coal fly ash produced from pulverized coal combustion in thermal power plants. Similar particle size ranges have been reported in previous studies on coal fly ash, where the majority of particles were observed to fall within the silt-sized fraction (<63 µm) (Querol et al., 2001; Blissett & Rowson, 2012).

The fine particle size is an important factor controlling the environmental behavior of fly ash. Small particles possess a higher specific surface area, which enhances their reactivity and adsorption capacity for various chemical species. Consequently, these particles can facilitate the dissolution and mobilization of trace metals when exposed to environmental conditions such as rainfall, groundwater infiltration, or atmospheric moisture (Jankowski et al., 2006). Moreover, fine particles can be easily transported by wind, potentially contributing to atmospheric dispersion and deposition of contaminants in surrounding environments (Izquierdo & Querol, 2012).

The values of water content and pH were 3.5% and 12.2 respectively. These results are in agreement with the previous studies (Akar et al., 2012; Yilmaz, 2015). In addition, most of studies have shown that the pH of fly ash was basic (Baba et al., 2003; Kim et al., 2003). The alkaline character of fly ash has also been widely reported in the literature (Baba et al., 2003; Kim et al., 2003; Jankowski et al., 2006). This high pH results mainly from the hydration and dissolution of calcium-bearing minerals formed during coal combustion. The alkaline conditions can influence the mobility and speciation of heavy metals. In many cases, alkaline environments may initially reduce metal mobility through precipitation reactions; however, under certain geochemical conditions, some metal ions may remain soluble or form stable complexes, leading to potential environmental risks (Adriano et al., 2002; Izquierdo & Querol, 2012).

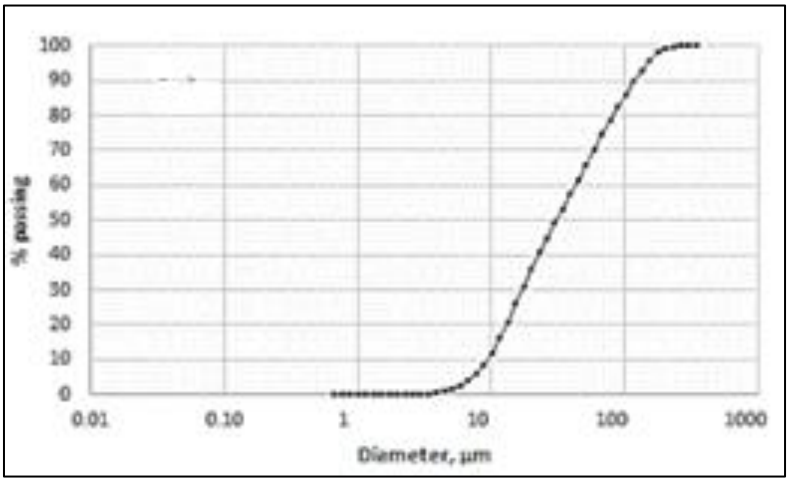

Figure 3 Size distribution of Yatağan fly ash sample

3.2. Chemical Properties of Fly Ash

Figure 4 and Table 2 present the mineralogical composition of fly ash sample which contains quartz (SiO_2), albite ($NaAlSi_3O_8$), anhydrite ($CaSO_4$), gehlenite ($Ca_2Al[AlSiO_7]$), lime (CaO), and hematite (Fe_2O_3). In addition, the principal mineral compound is quartz and the secondary minerals are albite, anhydrite, and gehlenite. Similarly, study was mentioned the similar findings from the mineralogical characterization from coal fly ash (Yilmaz, 2015).

Table 2 Results of chemical composition

Major elements	Percentage of major elements
SiO_2	52.74
Al_2O_3	18.34
Fe_2O_3	6.19
CaO	13.26
MgO	2.24
Na_2O	0.62
K_2O	2.35
MnO	0.05
TiO_2	0.77
SO_3	2.38
LOI	1.38

The predominance of quartz in fly ash samples is commonly attributed to the presence of siliceous minerals in the original coal feedstock, which remain relatively stable during combustion processes (Querol et al., 2001). Albite and gehlenite are typical aluminosilicate minerals formed through high-temperature transformations of clay minerals during coal combustion. Anhydrite is generally produced by the oxidation of sulfur compounds present in coal, followed by reactions with calcium-bearing minerals under combustion conditions (Vassilev & Vassileva, 2007).

The formation of these mineral phases reflects the complex thermochemical reactions occurring during coal combustion at temperatures ranging between 800 and 1500 °C. During this process, clay minerals such as kaolinite, illite, and montmorillonite undergo dehydroxylation, melting, and recrystallization to form new crystalline and amorphous phases (Blissett & Rowson, 2012). The mineralogical composition of fly ash is therefore strongly influenced by the mineralogy of the original coal, combustion temperature, and cooling rate of the ash particles (Izquierdo & Querol, 2012).

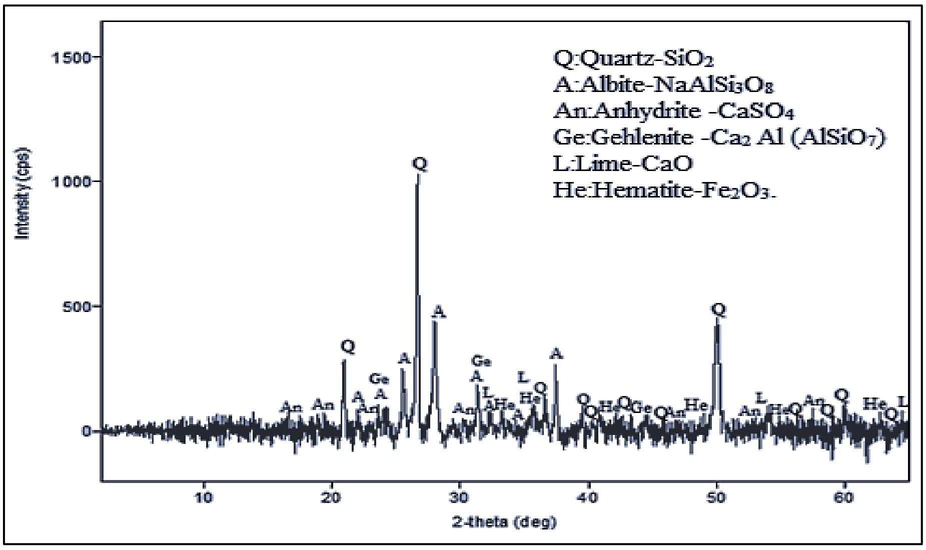

Figure 4 X-ray diagram of fly ash sample

The following **Table 3** presents the concentrations of trace elements (i.e., heavy metals) and non-trace elements.

Table 3 Results of chemical analysis of fly ash sample**.**

Heavy metal	Heavy metal concentrations (mg/kg)
Cd	2.9
Co	Nd
Cr	137.3
Cu	73.0
Fe	116.8
Mn	321.4
Ni	82.8
Pb	Nd
Sr	297.0
Zn	98.4

The results from wet analysis indicate the presence of several hazardous metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sr, and Zn) in industrial and mining samples with high concentrations. For instance, the determined hazardous metals such as 2.9 mg/Kg of Cd, 73.0 mg/kg of Cu, 82.8 mg/Kg of Ni, 137.3 mg/Kg of Cr, 321.4 mg/Kg of Mn exceed the permissible concentration for waste disposal which their concentrations were 1 mg/kg for Cd, 75 mg/kg for Cr, 50 mg/Kg of Cu, 50 mg/Kg of Ni 100 mg/kg of Mn as (Ashfaq et al., 2025; Vareda et al., 2019; Yatoo et al., 2024). According to Akar et al., (2012) as the pH is an important parameter for metal dissolution, their interactions with water and air can generate the environmental pollution. For example, the dissolution of certain metals ions like Cd, Cr and Zn are effective in pH above 7 (Akar, 2001; Kim, 2006; Koukouzas, et.al; 2011; Zandi and Russel, 2007). Researchers have demonstrated that heavy metals from fly ash have high solubility rate due to fine particles of fly ash sample (Bhattacharyya et al., 2009; Jankowski et al., 2006; Querol et al., 2000; Weng & Huang, 2004).

Furthermore, the high solubility rate of heavy metals from fly ash is often associated with the fine particle size and large surface area of the material. Fine particles enhance leaching processes and increase the likelihood of metal migration into surrounding environmental compartments (Bhattacharyya et al., 2009; Weng & Huang, 2004). This phenomenon represents a significant environmental concern, particularly in areas where fly ash is disposed of in open landfills or ash ponds without adequate containment systems.

4. Conclusion

The characterization of the studied fly ash provides important information regarding its physicochemical properties and potential environmental impacts. The experimental results reveal that the fly ash contains significant concentrations of heavy metals, including 2.9 mg/kg of Cd, 73.0 mg/kg of Cu, 82.8 mg/kg of Ni, 137.3 mg/kg of Cr, and 321.4 mg/kg of Mn. These concentrations exceed several recommended environmental limits and may pose potential risks to soil and groundwater systems.

Due to its fine particle size and alkaline pH, the fly ash has the potential to release heavy metals through leaching processes when exposed to water and atmospheric conditions. Such processes may contribute to environmental contamination and, in some cases, generate acid mine drainage or other forms of pollution affecting ecosystems and human health.

Therefore, regular monitoring and proper management of fly ash disposal sites are essential to minimize environmental risks. In addition, stabilization and immobilization techniques, such as the use of phosphate-based materials or other chemical amendments, may be applied to reduce the mobility of heavy metals and improve the environmental sustainability of fly ash management in thermal power plants.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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