Chapter 6
Strategies for Collection, Treatment, and Recycling of Fly Ash from Thermal Power Plants

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Abstract Coal-based thermal power plants cater to a larger fraction of power generation and supply in developing countries including India. However, after electrostatic precipitation of finer ash particles from flue gases, a huge amount of fly ash is produced in these plants as a solid waste. The fly ash consists of silica, alumina, oxides of iron, calcium, magnesium, heavy metals, and organic compounds. The disposal of fly ash in conventional ash ponds and landfills may further cause soil and groundwater pollution and requires proper management. This chapter provides a detailed review about the pollutions caused by the fly ash as well as current strategies for their collection, treatment, and recycling. Different strategies of recycling and reuse are reviewed and discussed including applications for construction materials and in pollution abatement, thus acting as a useful resource rather than a waste product.

Keywords Fly ash · Thermal power plant · Heavy metals
Soil and water pollution · Recycling

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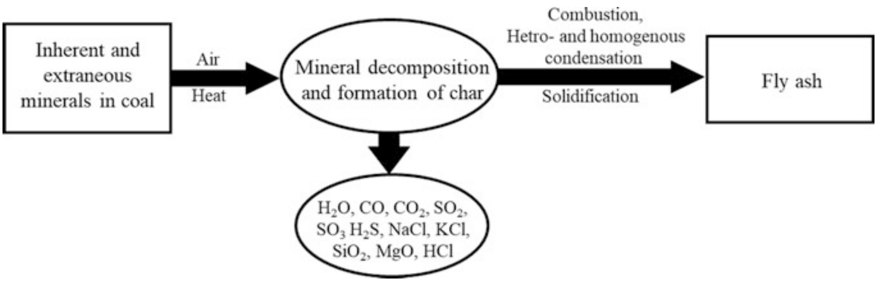
6.1 Introduction

Thermal power plants have been historically instrumental for power generation in majority of countries, including India, and still contribute significantly toward their economic growth. In India, these plants contribute toward more than 50% of the electricity generation. Also, a very significant portion of this (>80%) is achieved with coal-based thermal power plants, where the pulverized coal is burnt, and the energy generated through this combustion is finally converted to electricity (GoI 2018). In this combustion process, different inorganic minerals present in the coal (e.g., clay, shale, quartz, feldspar, etc.) melt and fuse together. Some of these fused minerals get suspended with combustion gases, and after cooling, solidify into particles (Scheme 6.1). These suspended particles in the exhaust gases are collectively called as fly ash (Ondova et al. 2012) and form a significant portion of the waste material from such power plants. For example, in India, 40% of the coal used in thermal power plants is converted to fly ash (Pandey et al. 2011).

The generated fly ash is a heterogeneous mixture of minerals with wide variation in physical and chemical properties that depend on the type of coal and production process among other factors. The size of fly ash particles varies from 10^{-8} to 10^{-4} m, with different colors, ranging from gray to black depending on the fraction of unburnt carbon present. Also, many of these minerals do not get time to recrystallize during the cooling process, and hence fly ash contains a significant portion of amorphous materials. Fe_2O_3, SiO_2, Al_2O_3, and CaO are some typical constituents in fly ash (Shehata et al. 1999).

Due to their diverse characteristics and compositions, a proper management of fly ash is challenging. Further, due to the presence of trace elements, heavy metals (Chaudhary and Banerjee 2007), and toxic organic compounds (Ribeiro et al. 2014), a direct disposal of this fly ash into different environmental matrices, viz. water, air, and land, in an unscientific manner, creates numerous environmental issues. Following sections discuss various environmental concerns with disposal of fly ash and the means for proper collection and treatment. Further, various applications toward sustainable management of fly ash are also discussed.



Scheme 6.1 Schematic of the coal fly ash formation mechanism from pulverized fuel combustion

6.2 Fly Ash as an Environmental Pollutant

In addition to various pollutant gases, viz. SO_x and NO_x, fly ash forms a major part of the exhaust gases from coal-based thermal power plants and if not managed properly may result in significant environmental pollution (He et al. 2012). This is due to the presence of various heavy metals, e.g., As, Ba, Cr, Se, Hg, etc., and adsorbed or deposited organic compounds (e.g., PAHs) on particle surfaces (Chaudhary and Banerjee 2007; Ribeiro et al. 2014).

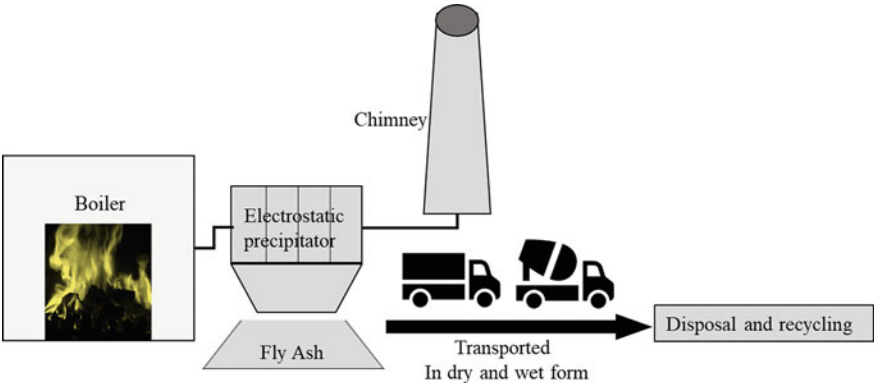
Inhalation is the most direct and important route of exposure to fly ash in humans since a significant portion of particulate matter ($PM_{2.5}$ and PM_{10}) in the atmosphere is contributed from coal fly ash (Kim et al. 2015). Further, such particulate matters have well-recognized health hazards including respiratory and cardiovascular diseases as well as premature mortality (Kim et al. 2015; Davidson et al. 2005). Coal fly ash, in particular, poses a significant health risk due to the very heterogeneous composition and presence of multiple heavy metals and toxic compounds. Sufficient data is now available which links the health risks to the communities living in the vicinity of coal thermal power plants to the inhalation exposure to the coal fly ash being emitted into the atmosphere.

The emitted fly ash further contaminates the receiving land and water bodies. For example, a significant accumulation of heavy metals, viz. As, Cd, Cr, Ba, Hg, etc., in the soil was directly linked to the fly ash deposition from coal power plant in Santaldih, West Bengal, India (George et al. 2015). Once enriched in the soil, multiple exposure pathways (viz. ingestion, inhalation, dermal contact, and consumption of contaminated vegetation, etc.) exist. In addition, the enrichment of these toxic elements in topsoil further deteriorates the soil quality. Leaching and runoff with rainwater is also a serious concern, and can potentially contaminate the surface and groundwater depending on the site geology and prevalent redox conditions (Spadoni et al. 2014).

6.3 Collection and Disposal of Fly Ash

A proper collection and disposal system of fly ash is important to effectively address the associated environmental concerns. The collection of fly ash from flue gases is normally done using electrostatic precipitators (ESP) and fabric filters (baghouses) (Al-Hamouz 2014). ESPs are installed near the chimney, where fly ash particles are charged at high voltage and then collected through electrostatic attraction at oppositely charged electrodes. The separated particles are then scraped from the electrode and collected in hoppers at the bottom (Scheme 6.2).

The collected fly ash is then transported to disposal sites either in a wet slurry or dry form. A high concentration slurry disposal (HCSD) system is generally adopted (Chandel et al. 2009) in which collected fly ash is fed to the mixing tank after conditioning. A uniform slurry of this conditioned ash is made by adding required



Scheme 6.2 Scheme of fly ash production in a conventional thermoelectric power plant

amount of water to achieve the desired characteristics. Ash concentration is maintained at 60% or above (w/w) in this high concentration slurry. Afterward, the uniform slurry is transferred through high concentration slurry disposal (HCSD) pump up to the ash dyke through seamless pipelines, where it is disposed on a slope. The disposed slurry spreads over a substantial area and solidifies.

A recent trend in power plants is to collect the fly ash in dry form and utilize it in various applications as raw material. Dry fly ash from ESPs and baghouses is collected in ash vessels. A free flow of dry ash in ash vessels is maintained using electric heaters. The heaters maintain the temperature well above the ash fusion temperature to prevent the formation of clusters of ash and ensure smooth functioning of the conveying system. The ash is further transported to fly ash silos with the help of compressed air. The moisture from the compressed air is removed using an adsorbent air dryer or refrigeration air dryer. Finally, the ash is transported into sealed vessel trucks.

6.4 Treatment

The combustion of coal during the power generation results in the heavy metal and organic micropollutants release with fly ash. This fly ash should go through treatment before landfilling or recycling (Eleonora and Margarida 2016). Some of the treatment methods are discussed below in detail.

6.4.1 Washing Process

Washing with water leads to removal of soluble salts. Further, the resulted solution could be evaporated to produce salt (Francois and Criado 2007; Chimenos et al. 2005; Nzihou and Sharrock 2002). The washing with water released heavy metals (e.g., Pb and Zn) along with the soluble salts. Wang et al. have shown the release of ~1% of Pb and other heavy metals with water, whereas another study by Weibel et al. have shown enhanced metal removal with acid water (Wang et al. 2009; Weibel et al. 2018). The metals in the fly ash also could be immobilized by chemical additives, such as soluble phosphates, which react with metals and form insoluble metal complexes (Uchida et al. 1996).

6.4.2 Leaching

Leaching process could be used to extract the metal ions from fly ash. Addition of chemical agents promotes faster leaching of heavy metals from the fly ash. Sabbas et al. presented the effect of pH on leaching (Sabbas et al. 2003) and showed that pH is strongly affecting the leaching process. Three main leaching behaviors have been shown in the literature: (1) cation-forming species and non-amphoteric metal ions (e.g., Cd); (2) amphoteric metals (including Al, Pb, and Zn) increase solubility under both strong acidic and strong alkaline conditions; and (3) oxyanion-forming metals (e.g., As, Cr, Mo, V, B, and Sb) decrease solubility in alkaline ranges ($pH > 10$) (Sabbas et al. 2003; Van der Bruggen and Vandecasteele 2003).

6.4.3 Electrochemical Processes

The main advantage of electrochemical processes is no requirement of additional chemicals. Temperature, current density, mixing conditions, the distance between the electrodes, and the pH of the solution were identified as main parameters which affect the electrochemical treatment process. Pedersen et al. showed an electrochemical treatment process named as electrodialytic remediation, which could be effectively used for the remediation of heavy metals and chlorides from fly ashes. It has been introduced as a new possible extraction method (Pedersen et al. 2005, 2003).

6.4.4 Thermal Treatment

This technique could be used for eliminating heavy metals through evaporation processes where the temperature was raised (less than melting point). This technique also allows recycling of the metals at the same time of evaporation. Jakob et al. examined the evaporation of heavy metals at 1000–1100 °C temperature. The Pb, Cd, and Cu have shown ~98% evaporation efficiencies, and the evaporated amounts and evaporation rates were strongly influenced by chlorides (Jakob et al. 1995). Stucki and Jakob showed that under reduced condition addition of chlorine gas can evaporate ~99% of the metals present in fly ash (evaporated as metal chlorides), and they can be collected separately as heavy metal condensates (Jakob et al. 1996).

6.4.5 Solidification

Solidification treatments are among the most widespread processes used for waste incineration remainders (Tang et al. 2016; Diaz-Loya et al. 2012). The principal purpose of solidification is to immobilize hazardous components in the fly ash. The binder materials (e.g., Portland cement) used for solidification not only hardens the hazardous waste by chemical means but also immobilize it by making stable complexes. These complexes are solids and either non-hazardous or less hazardous than the original waste by encapsulating the pollutants which leads to low permeability.

6.4.6 Chemical Stabilization

Chemical stabilization involves chemical precipitation of heavy metals into insoluble composites or heavy metal complex with various mineral species or chemical agents. The main chemical agents used for stabilization include sulfides (Katsuura et al. 1996), soluble phosphates (Nzihou and Sharrock 2002; Derie 1996; Eighmy et al. 1997), ferrous iron sulfate (Lundtorp et al. 2002), and carbonates (Ecke et al. 2003). Chemical stabilization leads to the substantial decrease in trace metal elements (Sabbas et al. 2003; Bayuseno and Schmahl 2011; Cornelis et al. 2008).

6.5 Recycling of Fly Ash: Applications

Fly ash collected from different parts of power plants has different properties and could be used for various applications, which are discussed below in detail.

ESP ash/chimney ash/dry fly ash: It is best suited for manufacturing of cement and other construction materials. In cement, fly ash could be used as cementitious materials (Lee et al. 1999). The other construction materials can also be made, e.g., fly ash bricks (without clay), blocks, pavers, sheets for roofing, tiles, etc (Mandal and Mandal 1996; Shanthakumar et al. 2008).

Bottom ash: Due to the coarse size of bottom ash, it is suitable for geotechnical applications, e.g., landfilling, construction of barriers, road and flyover bridges, etc (Chang and Wey 2006). Bottom ash could be also used as a substitute for the sand in mortar and concrete after the removal of organic carbon (Chindaprasirt et al. 2009).

Pond ash: Pond ash has a medium grain size, which is mainly the mixture of ESP and bottom ash. Agriculture, wasteland development, and forestry are the best suited for pond ash applications, and it can also be used for geotechnical applications. Protocols have been established to construct bricks with pond ash and clay mixture. Another important utilization of pond ash is in the manufacturing of clay bricks. It has been shown that 30–80% of clay can be mixed with pond ash and will result to improve quality, which reduces the breakage during transportation. This ash is also suitable for ceramic products (Chang and Wey 2006; Ghosh 2009; Kumar Bera et al. 2007). Fly ash could be effectively used as construction materials as discussed below.

6.5.1 Constructive Materials

Fly ash has been highly used as a supplementary cementitious material (SCM) in the construction of Portland cement. Fly ash use as a SCM in concrete has been started in last century (Thomas 2007; Newman 1979), especially after the pioneering research conducted by Davis et al. at the University of California, Berkeley in 1937 (Dreher et al. 1997; Chindaprasirt et al. 2008; Thomas et al. 2002). In the last 50 years, fly ash use in concrete grows dramatically. In 2005, $\sim$15 million tons of fly ash was used in concrete, concrete products, and grouts in the USA alone (Edil et al. 2006). There are many drawbacks such as slower strength gain, higher salt scaling, and benefits such as high strength gain, reduced heat of hydration, and denser concrete with smooth surfaces for fly ash as construction materials.

At present, more than 50% of the concrete has fly ash in the USA. The dosages varied with the quality of the fly ash (15–40%) in the concrete. There are mainly two types of fly ashes used in the concrete which are Class C and Class F fly ash. Both types of fly ashes react with concrete in similar ways except that of Class C that has enough lime to undergo self-cementing. The chemical composition of Class C, Class F, and Portland cement chemical is shown in Table 6.1.

Lightweight construction products from fly ash have many advantages such as low costs of shipping as compared to the non-light weight product. The reduced

Table 6.1 A brief description of the chemical composition of fly ash and Portland cement (American Coal Ash Association 2003)

Compounds	Fly ash Class F	Fly ash Class C	Portland cement
SiO_2	55	40	23
Al_2O_3	26	17	4
Fe_2O_3	7	6	2
CaO (Lime)	9	24	64
MgO	2	5	2
SO_3	1	3	2

cost is visible for bricks as fly ash bricks weigh one-third of the conventional clay-fired bricks (Sharma and Dhir 2015) leading to reduced shipping costs (Rajgor et al. 2013). The fly ash bricks may appear expensive than conventional products but the final financial benefit should be evaluated in terms of its increased physical properties, chemical properties, and environmental benefits. Bricks from fly ash and clay mixture are more porous than fly ash bricks, and results in high strength than fly ash bricks. Fly ash brick manufacturing units could be set up near thermal power stations to make it cost-effective. These manufacturing units can get free fly ash from the power plants. Nowadays, there is good demand for fly ash bricks. The awareness among the people is required for better results along with government support. This technology is eco-friendly as it reduces solid waste and dust in the environment as well as the cost is quite comparable to conventional bricks. Fly ash could be also used for the construction of roads. The fly ash could be used in the earthen core which prevents the heavy metal leaching as fly ash reacts with cement and reduces any leaching effect. Hence, chances of pollution due to the use of fly ash in roads are negligible.

6.6 Pollution Abatements by Fly Ash

Fly ash could be used as an effective absorbent for the abatement of pollutants, e.g., SO_x, NO_x, metals, and other pollutants.

6.6.1 Adsorbents for Flue Gas

Generally, SO_x emission is controlled by installing wet-type limestone scrubbers and as a result of it, high desulfurization efficiency and easy operation can be achieved. But this process has high water consumption resulting in wastewater generation which needs further treatment, whereas dry-type flue gas desulphurization (FGD) has advantages as no wastewater is generated in this process but it requires large amount of adsorbent. Fly ash could be effectively used for dry-type FGD as it is available in large amount. Similar to SO_x, NO_x could be effectively removed using fly ash. NO_x adsorption into fly ash depends on the carbon content and specific surface area. The unburnt carbon in the fly ash contributes maximum in the specific surface area, which could be further activated through gasification for the higher adsorption. For better activation of fly ashes, minerals should be removed before the activation of fly ashes to avoid interference.

6.6.2 Adsorption of Various Types of Heavy Metals and Fluorides on Fly Ash

Researchers have shown the potential of fly ash for heavy metal removal (Bhattacharya et al. 2008; Gupta et al. 1998, 2011; Yadava et al. 1987). The most studied metals are Hg, Cr, Ni, Pb, As, Cu, and Cd. Enhanced mercury adsorption was reported after oxidizing the unburnt carbon in the fly ash at 400 °C (Li and Maroto-Valer 2012). This confirmed the important role of oxygen-containing functional groups in the adsorption process. In another study, Masaki et al., have shown the effect of calcium chloride and activated carbon concentration with synthetic fly ash on the adsorption of mercury, and best result was obtained for 5–7% in synthetic fly ash with 1% calcium chloride (Takaoka et al. 2000). There are many studies for removal of Cr(VI) and Cr(III) using fly ash as adsorbent and established the effect of fly ash dosages, contact time, and pH on the removal of chromium (Bhattacharya et al. 2008; Gupta et al. 1998; Gupta et al. 2011). Pandey et al., have used fly ash and wollastonite (1:1) mixture for the removal of chromium (Panday et al. 1984). Bayat et al., have shown higher adsorption capacity for Cd(II) as compared to Cr(VI) in a mixture with fly ash and crystalline CaO in fly ash significantly affect the adsorption of Cr(VI) and Cd(II) (Bayat 2002). Chromium and nickel were effectively removed by low-cost adsorbent made from raw bagasse and fly ash (Rao et al. 2002). The metal adsorption by fly ash was strongly dependent on the experimental system, and physical and chemical characteristics of the adsorbent and adsorbate (Babel and Kurniawan 2003).

Several studies have been reported for the removal of fluoride from waters using fly ash (Chaturvedi et al. 1990; Nemade et al. 2002). Chaturvedi et al. showed the effect of different concentrations, contact times, temperatures, and pH of the solution on the removal of fluoride from contaminated water (Chaturvedi et al. 1990; Nemade et al. 2002). A column study has shown complete removal of fluoride in 120 h for low concentration of fluoride and in 168 h with the high concentration of fluoride (Nemade et al. 2002; Tor et al. 2009).

6.7 Summary and Future Prospects

This chapter reviewed various strategies for collection, treatment, and recycling of fly ash from coal-based thermal power plants. The requirement of proper ash management system is also identified to address the related environmental concerns with ash disposal. Certain applications where fly ash is utilized as a resource are also discussed. Fly ash has shown potential to be used as construction material as well as an adsorbent for pollution abatement. However, majority of the studies are conducted at lab scale and limited information is available for their large-scale application.

Based on the review of the literature, the following future research directions are identified:

- Industrial scale applications of fly ash for pollution abatement have been not established till date, so there is an urgent need to scale up the fly ash application. In general, fly ash has low adsorption capacity and need modification to enhance the adsorption capacity and mass production should reduce the cost effectively.
- Similarly, for construction purposes, there is a need for well-established protocols for effective use of different types of fly ashes.
- There are many other products where fly ash could be used as initial raw materials such as geopolymers, mullite, and quartz–cristobalite–tridymite. Such novel applications at large scale need to be further investigated for proper utilization of fly ash.
- Full-scale application of fly ash to enrich agriculture soil is needed.
- Life cycle assessment and environmental impact assessment are required for different fly ash products to assess long-term benefits and disadvantages.

References

Al-Hamouz Z (2014) Numerical and experimental evaluation of fly ash collection efficiency in electrostatic precipitators. Energy Convers Manag 79:487–497

American Coal Ash Association (2003) Fly ash facts for highway engineers, 1–74

Babel S, Kurniawan TA (2003) Low-cost adsorbents for heavy metals uptake from contaminated water: a review. J Hazard Mater 97(1–3):219–243

Bayat B (2002) Comparative study of adsorption properties of Turkish fly ashes: II. The case of chromium (VI) and cadmium (II). J Hazard Mater 95(3):275–290

Bayuseno AP, Schmahl WW (2011) Characterization of MSWI fly ash through mineralogy and water extraction. Resour Conserv Recycl 55(5):524–534

Bhattacharya A, Naiya T, Mandal S, Das S (2008) Adsorption, kinetics and equilibrium studies on removal of Cr (VI) from aqueous solutions using different low-cost adsorbents. Chem Eng J 137(3):529–541

Chandel S, Seshadri V, Singh SN (2009) Effect of additive on pressure drop and rheological characteristics of fly ash slurry at high concentration. Part Sci Technol 27:271–284

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

Chaturvedi A, Yadava K, Pathak K, Singh V (1990) Defluoridation of water by adsorption on fly ash. Water Air Soil Pollut 49(1–2):51–61
Chaudhary S, Banerjee DK (2007) Speciation of some heavy metals in coal fly ash. Chem Speciat Bioavailab 19(3):95–102
Chimenos J, Fernández A, Cervantes A, Miralles L, Fernández M, Espiell F (2005) Optimizing the APC residue washing process to minimize the release of chloride and heavy metals. Waste Manag 25(7):686–693
Chindaprasirt P, Rukzon S, Sirivivatnanon V (2008) Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash. Constr Build Mater 22(5):932–938
Chindaprasirt P, Jaturapitakkul C, Chalee W, Rattanasak U (2009) Comparative study on the characteristics of fly ash and bottom ash geopolymers. Waste Manag 29(2):539–543
Cornelis G, Johnson CA, Van Gerven T, Vandecasteele C (2008) Leaching mechanisms of oxyanionic metalloid and metal species in alkaline solid wastes: a review. Appl Geochem 23 (5):955–976
Davidson CI, Phalen RF, Solomon PA (2005) Airborne particulate matter and human health: a review. Aerosol Sci Technol 39(8):737–749
Derie R (1996) A new way to stabilize fly ash from municipal incinerators. Waste Manag 16 (8):711–716
Diaz-Loya EI, Allouche EN, Eklund S, Joshi AR, Kupwade-Patil K (2012) Toxicity mitigation and solidification of municipal solid waste incinerator fly ash using alkaline activated coal ash. Waste Manag 32(8):1521–1527
Dreher KL, Jaskot RH, Lehmann JR, Richards JH, Ghio JKMAJ, Costa DL (1997) Soluble transition metals mediate residual oil fly ash induced acute lung injury. J Toxicol Environ Health Part A 50(3):285–305
Ecke H, Menad N, Lagerkvist A (2003) Carbonation of municipal solid waste incineration fly ash and the impact on metal mobility. J Environ Eng 129(5):435–440
Edil TB, Acosta HA, Benson CH (2006) Stabilizing soft fine-grained soils with fly ash. J Mater Civ Eng 18(2):283–294
Eighmy TT, Crannell BS, Butler LG, Cartledge FK, Emery EF, Oblas D, Krzanowski JE, Eusden JD, Shaw EL, Francis CA (1997) Heavy metal stabilization in municipal solid waste combustion dry scrubber residue using soluble phosphate. Environ Sci Technol 31(11): 3330–3338
Eleonora L, Margarida J (2016) Chemical stabilization of municipal solid waste incineration fly ash without any commercial chemicals: first pilot-plant scaling up. ACS Sustain Chem
Francois D, Criado C (2007) Monitoring of leachate at a test road using treated fly ash from municipal solid waste incinerator. J Hazard Mater 139(3):543–549
George J, Masto RE, Ram LC, Das TB, Rout TK, Mohan M (2015) Human exposure risks for metals in soil near a coal-fired power-generating plant. Arch Environ Contam Toxicol 68 (3):451–461
Ghosh A (2009) Compaction characteristics and bearing ratio of pond ash stabilized with lime and phosphogypsum. J Mater Civ Eng 22(4):343–351
GoI (2018) Annual report 2017–18, pp 1–276. Ministry of Power, Government of India
Gupta VK, Mohan D, Sharma S, Park KT (1998) Removal of chromium (VI) from electroplating industry wastewater using bagasse fly ash—a sugar industry waste material. Environmentalist 19(2):129–136
Gupta V, Agarwal S, Saleh TA (2011) Chromium removal by combining the magnetic properties of iron oxide with adsorption properties of carbon nanotubes. Water Res 45(6):2207–2212
He Y, Luo Q, Hu H (2012) Situation analysis and countermeasures of China's fly ash pollution prevention and control. Procedia Environ Sci 16:690–696

Jakob A, Stucki S, Kuhn P (1995) Evaporation of heavy metals during the heat treatment of municipal solid waste incinerator fly ash. Environ Sci Technol 29(9):2429–2436

Jakob A, Stucki S, Struis RPWJ (1996) Complete heavy metal removal from fly ash by heat treatment: influence of chlorides on evaporation rates. Environ Sci Technol 30(11):3275–3283

Katsuura H, Inoue T, Hiraoka M, Sakai S (1996) Full-scale plant study on fly ash treatment by the acid extraction process. Waste Manag 16(5–6):491–499

Kim K-H, Kabir E, Kabir S (2015) A review on the human health impact of airborne particulate matter. Environ Int 74:136–143

Kumar Bera A, Ghosh A, Ghosh A (2007) Compaction characteristics of pond ash. J Mater Civ Eng 19(4):349–357

Lee SH, Sakai E, Daimon M, Bang WK (1999) Characterization of fly ash directly collected from electrostatic precipitator. Cem Concr Res 29(11):1791–1797

Li J, Maroto-Valer MM (2012) Computational and experimental studies of mercury adsorption on unburned carbon present in fly ash. Carbon 50(5):1913–1924

Lundtorp K, Jensen DL, Christensen TH (2002) Stabilization of APC residues from waste incineration with ferrous sulfate on a semi-industrial scale. J Air Waste Manag Assoc 52 (6):722–731

Mandal PK, Mandal TK (1996) Electrostatic precipitator performance in Indian pulverized coal based thermal power stations: problems and solutions. Water Energy Res Dig 19(4):31–40

Nemade P, Rao AV, Alappat B (2002) Removal of fluorides from water using low cost adsorbents. Water Sci Technol Water Supply 2(1):311–317

Newman JR (1979) Effects of industrial air pollution on wildlife. Biol Cons 15(3):181–190

Nzihou A, Sharrock P (2002) Calcium phosphate stabilization of fly ash with chloride extraction. Waste Manag 22(2):235–239

Ondova M, Stevulova N, Estokova A (2012) The study of the properties of fly ash based concrete composites with various chemical admixtures. Procedia Eng 42:1863–1872

Panday K, Prasad G, Singh V (1984) Removal of Cr (V1) from aqueous solutions by adsorption on fly ash-wollastonite. J Chem Technol Biotechnol 34(7):367–374

Pandey VC, Singh JS, Singh RP, Singh N, Yunus M (2011) Arsenic hazards in coal fly ash and its fate in Indian scenario. Resour Conserv Recycl 55(9):819–835

Pedersen AJ, Ottosen LM, Villumsen A (2003) Electrodialytic removal of heavy metals from different fly ashes: influence of heavy metal speciation in the ashes. J Hazard Mater 100 (1–3):65–78

Pedersen AJ, Kristensen IV, Ottosen LM, Ribeiro AB, Villumsen A (2005) Electrodialytic remediation of CCA-treated waste wood in pilot scale. Eng Geol 77(3–4):331–338

Rajgor MB, Makwana AH, Pitroda J (2013) Automation in clay and thermal industry waste products. Int J Eng Trends Technol 4(7):2870–2877

Rao M, Parwate A, Bhole A (2002) Removal of Cr^{6+} and Ni^{2+} from aqueous solution using bagasse and fly ash. Waste Manag 22(7):821–830

Ribeiro J, Silva TF, Mendonça Filho JG, Flores D (2014) Fly ash from coal combustion—an environmental source of organic compounds. Appl Geochem 44:103–110

Sabbas T, Polettini A, Pomi R, Astrup T, Hjelmar O, Mostbauer P, Cappai G, Magel G, Salhofer S, Speiser C (2003) Management of municipal solid waste incineration residues. Waste Manag 23(1):61–88

Shanthakumar S, Singh D, Phadke R (2008) Influence of flue gas conditioning on fly ash characteristics. Fuel 87(15–16):3216–3222

Sharma S, Dhir AG (2015) Assessment of the use of steel slag and/or air pollution control devices dust in the manufacturing of fly ash bricks/blocks

Shehata MH, Thomas MDA, Bleszynski RF (1999) The effects of fly ash composition on the chemistry of pore solution in hydrated cement pastes. Cem Concr Res 29(12):1915–1920

Spadoni M, Voltaggio M, Sacchi E, Sanam R, Pujari PR, Padmakar C, Labhasetwar PK, Wate SR (2014) Impact of the disposal and re-use of fly ash on water quality: the case of the Koradi and Khaperkheda thermal power plants (Maharashtra, India). Sci Total Environ 479–480:159–170

Takaoka M, Takeda N, Fujiwara T (2000) Experimental studies on the removal mechanism of mercury vapor by synthetic fly ash. J Jpn Soc Atmos Environ (Taiki Kankyo Gakkaishi) 35 (1):51–62

Tang Q, Liu Y, Gu F, Zhou T (2016) Solidification/stabilization of fly ash from a municipal solid waste incineration facility using Portland cement. Adv Mater Sci Eng

Thomas M (2007) Optimizing the use of fly ash in concrete, vol 5420. Portland Cement Association Skokie, IL

Thomas M, Hopkins D, Girn G, Munro R, Muhl E (2002) The use of high-volume fly ash in concrete. In: Proceedings, 7th international gypsum and fly ash science and technology conference, Toronto

Tor A, Danaoglu N, Arslan G, Cengeloglu Y (2009) Removal of fluoride from water by using granular red mud: batch and column studies. J Hazard Mater 164(1):271–278

Uchida T, Itoh I, Harada K (1996) Immobilization of heavy metals contained in incinerator fly ash by application of soluble phosphate—treatment and disposal cost reduction by combined use of "High Specific Surface Area Lime". Waste Manag 16(5–6):475–481

Van der Bruggen B, Vandecasteele C (2003) Removal of pollutants from surface water and groundwater by nanofiltration: overview of possible applications in the drinking water industry. Environ Pollut 122(3):435–445

Wang Q, Yang J, Wang Q, Wu T (2009) Effects of water-washing pretreatment on bioleaching of heavy metals from municipal solid waste incinerator fly ash. J Hazard Mater 162(2–3):812–818

Weibel G, Eggenberger U, Kulik DA, Hummel W, Schlumberger S, Klink W, Fisch M, Mäder UK (2018) Extraction of heavy metals from MSWI fly ash using hydrochloric acid and sodium chloride solution. Waste Manag

Yadava K, Tyagi B, Panday K, Singh V (1987) Fly ash for the treatment of Cd (II) rich effluents. Environ Technol 8(1–12):225–234