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A Review on the Utilization and Environmental Concerns of Coal Fly Ash

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ABSTRACT

Fly ash is a solid by-product from the pulverization of coal in thermal power plants. It is a cost-effective raw material that has gained so much attention from industrialists for a series of engineering purposes. It is utilized in various applications like cement and concrete, bricks, road construction and embankments, mine backfilling, mixed asphalt, soil amelioration, catalyst, production plants, geopolymers, etc. Asia and USA. are the top global fly ash producers. The high demand for its utilization adds to the economy of fly ash-producing nations. China, India, and Japan contribute to the fly ash market growth through urbanization and sustainable infrastructural activities. Fly ash is not environmentally friendly. It is currently one of the leading industrial solid wastes that has attracted so much public attention due to its associated environmental health concerns. It poses a severe social and economic burden to municipal and central authorities. COX, NOX, SOX, and matter are pollutants emitted from fossil fuel burning. Carbon dioxide and carbon monoxide are indirect agents of climate change. Fly ash contains heavy metals and some radioactive elements; therefore, utilizing it can lead to severe health and environmental consequences if not adequately managed.

INTRODUCTION

The global demand for fly ash utilization in buildings and infrastructure, agriculture, geopolymers, catalysts, etc is on the increase. Sustainable industrial and infrastructural development projects in Western nations influence the market growth of fly ash. According to sources from Vantage market research, the global fly ash market in 2021 was at USD 12.1 billion. Recently, many countries have been trying to shift away from using fossil fuel as a source to renewable energy technology to combat the environmental impacts of greenhouse gases (COx) emitted from burning fossil fuels in thermal power plants (Mucomole, Silva, & Magaia, 2023). This is a significant challenge for the growth of the fly ash market. However, developing new technologies to produce fly ash will possibly maintain a sustained fly ash market growth now and in the future. The key market players are now focusing on sustained practices to reduce emissions, and waste minimization, and utilize renewable energy sources(Hossain & Pk, 2023; Mucomole *et al.*, 2023).

It can also be recycled and used for multiple purposes rather than dumped or disposed of in open pits, landfills, and ponds. Using recycled fly ash for many farm practices contributes significantly to the growth of the fly ash market. Fossil fuel has the largest share and source of global electric power production. The utilization of coal for electricity generation is still widely embraced on a worldwide platform. In 2011, coal power supplied up to 29.9% of global energy, and this is projected to rise to 46% by 2030 (ARDHA & AZIZ, 2007). Coal-powered generation is economically attractive due to the high prices of oil and gas (Hossain & Pk, 2023; Lior, 2010). Pulverized fuel ash is a by-product that evolves out of coal-fired boilers with flue gases (Hossain & Pk, 2023; Rani, Rani, Bansal, Singh, & Singh, 2021). The waste residue is trapped by filtration equipment before the gases enter the chimneys (Rani *et al.*, 2021). The constituents in fly ash vary depending on the sources of the coal utilized (Ahmaruzzaman, 2010).

The health and environmental problems of fly ash are well-known. Open land disposal is the most common method adopted by coal power industries. Fly ash is regarded as a general solid waste in some countries. The concentrations, and solid/liquid ratio, affect trace elements in aqueous environments (Saikia, Kato, & Kojima, 2006). This threatens the air, surface, groundwater, soil, and crop production (ARDHA & AZIZ, 2007). In the early years of thermal power plant operations, fly ash was disseminated into the atmosphere with no control measures by the industries. The development of air pollution regulatory standards required fly ash to be trapped by pollution control equipment before being released and stored at the sites of power plants or landfills (Finkelman, Wolfe, & Hendryx, 2021).

Pozzolans provide better concrete protection from moist conditions and chemical attacks. Reports and findings from various scientific research (Sadik, El Amrani, & Albizane, 2014) reveal that fly ash can be utilized to fabricate refractory materials (cordierite, mullite, and kyanite) when combined with alumina and subjected to high temperatures. Manufactured refractory materials have a better advantage over other engineering materials utilized for various engineering purposes. This review summarizes fly ash utilization and associated health and environmental concerns. Fly ash is considered a worldwide environmental hazard since it contains organic and inorganic pollutants, toxic heavy metals (Pb Hg, Cr, V), and radionuclides.

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LITERATURE REVIEW

Fly ash is a fine-grained and powdered particulate matter obtained from the combustion of coal in a coal-fired boiler in thermal power plants. The electric power industry has three types of coal-fired boiler furnaces referred to as dry-bottom bottom boilers, wet-bottom boilers, and cyclone furnaces. It is an industrial solid waste that poses many environmental and storage issues in coal power-producing nations. It is nowadays popularly utilized as a mineral additive by construction companies as a low-cost material, reduces environmental pollution, and also helps in reducing the need for the utilization of natural resources.

Fly ash is available in two main classes. It is classified as class C or class F ash based on its chemical constituents particularly when used as a mineral admixture in concrete. It consists of significant amounts of SiO_2, Al_2O_3, Fe_2O_3, and CaO and smaller amounts of oxides of magnesium, potassium, sodium, titanium, and sulfur. Class C fly ash is produced from the combustion of lignite or sub-bituminous coal. It possesses pozzolanic and cementitious properties and contains more than 10% calcium oxide. It composes of higher amounts of alkali and sulfate (SO_4) compounds (Dwivedi & Jain, 2014). Class F fly ash is formed from anthracite or bituminous coal. It is naturally pozzolanic and contains less than 10% calcium oxide (CaO). Class F fly ash requires a cementing agent, such as Portland cement, quicklime, or hydrated lime, with water to produce cementitious compounds. Adding a chemical activator such as sodium silicate (water glass) to a Class F ash can lead to the formation of a geopolymer (Dwivedi & Jain, 2014).

Advantages and disadvantages of fly ash

Advantages of fly ash

It is a cost-effective substitute. It reduces the heat of hydration. The water required is reduced with better workability. It has low permeability and improved resistance to sulfate attack. It solves the problem of cracks experienced in Portland cement. Using fly ash in concrete reduces CO_2 and is thus a friendly environmental solid waste.

Disadvantages of fly ash

It changes from liquid to solid in a few hours after pouring. The air ingress reduces. The color of the concrete is more challenging to control. The use of fly ash increases salt scaling and experiences seasonal restrictions. Unlike Portland cement, it reduces the demand for waste.

Utilization and management of fly ash

Coal is the only natural resource widely used in thermal power plants to produce electricity (Mao & Xu, 1999). Industrialization, urbanization, and economic development are the major factors influencing the growing desire for electricity. Fly ash from pulverized coal has been proven to be a helpful waste material in many applications (Jala & Goyal, 2006; Rani *et al.*, 2021). Alumina and silica are the principal compounds, that make fly ash essential for profitable utilization. The ash from the coal plant is first processed using various techniques such as demagnetization, sinterization, grinding, etc. (Sukkae, Suebthawilkul, & Cherdhirunkorn, 2018). The utilization of fly ash can abate environmental threats, render income, create job opportunities, and provide a sustained cleaned-up environment, etc (Dwivedi & Jain, 2014; Finkelman *et al.*, 2021; L. C. Ram & Masto, 2010; Senapati, 2011). Mercury, lead, arsenic, etc., released into the environment, affect the quality of air, soil, and underground water (Yiwei *et al.*, 2007). The health risks of fly ash have led to several studies on its utilization in many applications, such as ceramic, bricks, landfills, and fly ash products, including ceramic refractories, plastics, metal composites, etc. (ARDHA & AZIZ, 2007). A tremendous amount of fly ash is annually produced, but utilization is minimal in many countries(ARDHA & AZIZ, 2007). The non-utilization of fly ash in many nations is due to some regulations that categorize fly ash as hazardous waste and the challenges of fabricating high-grade products (ARDHA & AZIZ, 2007). The utilization of fly ash in some applications and its management are discussed as follows:

Refractory

Due to their high-temperature resistance, refractory materials are used in furnace linings and metal-melting pots. The characteristics of fly ash have been studied, followed by examining the high-temperature resistance of materials mixed with fly ash and other silica-alumina source materials(ARDHA & AZIZ, 2007; Hwang, 1999). S. Maitra *et al.* (Maitra, Kumar, Vishwakarma, & Dutta, 2001) synthesized refractory aggregates from beneficiated fly ash by reaction sintering at 1600°C. The fly ash was discovered to be a good alumina-silica raw material based on castable refractory(Dana, Sinhamahapatra, Tripathi, & Ghosh, 2014).

Concrete

Fly ash is pozzolanic and it is used as a low-cost (Maitra *et al.*, 2001; Sukkae *et al.*, 2018) material compared to Portland cement. It is more environmentally friendly; it reduces the corrosion of steel and improves its resistance to chemical attacks. It can be used to construct underwater structures. Portland cement is the world's third-largest industrial consumer of energy; it is the second-highest CO_2 emitter with an estimated share of 8-10% of global emissions (da Silva, Malacarne, Longhi, & Kirchheim, 2021). The pozzolanic reaction between fly ash and lime produces less heat and hence reduces the possibility of thermal cracking (Dhadse, Kumari, & Bhagia, 2008; V. M. John, Quattrone, Abrao, & Cardoso, 2019; S. A. Miller, 2018; Shen, Wang, Li, Yao, & Jiang, 2020). The cement industry in India utilized about 60.11 million tons of total production in 2018 and 2019 (Dwivedi & Jain, 2014; Tejasvi & Kumar, 2012).

Soil Stabilization

Modifying soil properties temporarily enhances sub-grade stability to speed up construction (Association, 2003; S. K. John, Nadir, & Girija, 2021; Sun, Li, Zhao, Zhu, & Zhang, 2016). Xiaofei *et al.* (Sun *et al.*, 2016) reported that stabilization could change the properties of municipal solid waste. It is also used to treat a wide range of sub-grade materials, from expensive clays to granular materials. Mixing fly ash with soil plasticity results in a decrease in plasticity; the primary mechanism behind this is the change in the size of soil grains (Dwivedi & Jain, 2014).

Embarkment

Fly ash is more economical and environmentally friendly to be utilized as an alternative to topsoil for road embankments, and its suitability has proved successful in many cases. Construction and design require many favorable properties like lightweight (superior over weak subsoil), higher shear strength (more excellent stability), no lumps, usually moist, compacted characteristics under inclement weather, cost savings, etc. (Ghazali, Muthusamy, & Ahmad, 2019). This utilization has many advantages over conventional methods. It saves the topsoil and fills up low-lying areas thus created. The utilization of fly ash is affected by its properties such as grain size distribution, compaction characteristics, shear strength, compressibility, permeability, and frost susceptibility (L. C. Ram *et al.*, 2007; L. Ram *et al.*, 2006). Class F fly ashes are typically used in embarkment because they are obtained from anthracite and sub-bituminous coal, rich in silica, alumina, and iron oxide (L. C. Ram & Masto, 2010; L. C. Ram *et al.*, 2007). It is globally used as a structural fill material for highway embankments. However, the use of fly ash in road embankments has environmental concerns like soil erosion, dispersion of fly ash into the air by wind, and the leaching of heavy metals into the subsoil.

Bio-Amelioration of soil

Reports from some recent research indicated that fly ash has a better application when mixed with organic materials like cow manure, sludge, farm yard manure, sludge, crop residues, and organic composts(Yao *et al.*, 2015). A combination of fly ash and organic matter reduces heavy metals, kills pathogens in sludge, improves bulk density, porosity, and biological activity in the soil, and reduces the leaching of nutrients, which is beneficial for agricultural utilization (Tu *et al.*, 2022). Organic amendment applications provide anchorage and growth of the plant on a fly ash dumping site.

Agriculture

Fly ash improves soil fertility status, plant growth, and agricultural yield (Bayat, 2002a, 2002b; Bhattacharya, Iftikar, Sahariah, & Chattopadhyay, 2012; Gorai & Ash, 2018; Kishor, Ghosh, & Kumar, 2010). It improves soil texture properties, aeration (Page, Elseewi, & Straughan, 1979), water-holding capacity, and porosity(Kene, Lanjewar, Ingole, & Chaphale, 1991). It provides micronutrients such as Mo, B, Fe, Zn, Cu, etc. (Dinjus, Fornika, & Scholz, 1996; Khan & Wajid, 1996). Fly ash is used for the reclamation of sodic soils and acidic soils (Adriano, Page, Elseewi, Chang, & Straughan, 1980; Bhattacharya & Chattopadhyay, 2003; Haynes, 2009; S. Singh & Gupta, 2003). However, there are associated hazards such as the effects on human and grazing animals, groundwater pollution, and soil infertility due to high fly ash doses in agricultural fields. Radionuclide present in fly ash also causes radiochemical pollution.

Geopolymers

More recently, fly ash has been used as a compound in geopolymers, where the reactivity of the fly ash glasses generates a binder comparable to a hydrated Portland cement in appearance and properties but has porosity and reduced CO2 emission. The limited use of fly ash geopolymer is due to its low reactivity, which depends on the particle size, glass content, and composition(Kumar & Kumar, 2011).

Waste Treatment

Fly ash is combined with other alkaline materials to transform sewage sludge into organic fertilizer or biofuel (Bayat, 2002a, 2002b). It is used for domestic and industrial wastewater treatment and as a toxic metal adsorbent to remove industrial and poisonous wastes like dyes (Dasmahapatra, Pal, & Bhattacharya, 1998; Devi & Dahiya, 2006; Dutta, Basu, & DasGupta, 2003; Goswami & Das, 2000).

Wood Substitute Material

Fly ash can be a good substitute for doors, windows, ceilings, partitions, furniture, etc. The main objective for using fly ash as a wood substitute composite (i.e., fly ash geopolymer composites) is to reduce deforestation by using it as an alternative to timber products, which is very much required to save our environment (Khan & Wajid, 1996). The development of fly ash-based composites needs fly ash as filler and jute cloth reinforcement.

Management of coal fly ash

Fly ash is a residual waste from burning fossil fuel in thermal power plants and is globally recognized as problematic. Studies have reported that the estimated annual yield in India, China, Germany, and the UK are 112, 100, 40, and 15 million tons, respectively. Some challenges in managing fly ash are the vast land requirement for disposal and the contamination of groundwater (Twardowska, Szczepanska, & Stefaniak, 2003). Fly ash can be adequately managed when used in various applications like building and road construction, soil amelioration, glass ceramics, geopolymers, filling low-lying areas, bricks, Portland cement, and concrete. The management of fly ash as solid waste should concern regulatory bodies, with particular emphasis on utilization to keep our environment safe from its hazards. Power plants should also adopt adequate fly ash management systems due to the large space occupancy within the power plant area. The coal fly ash also contains significant amounts of toxic metals such as As, Ba, Hg, Cr, Ni, V, Pb, Zn, and Se, characteristically enriched in coal fly ash particles.

The environmental effects of coal fly ash

Emissions from the burning of fossil fuel

Carbon dioxide and Carbon monoxide

Outdoor and indoor fossil fuels are employed for global consumption and domestic energy purposes (Belyaeva & Haynes, 2012; J. Chen *et al.*, 2014; Yousuf, Manzoor, Youssouf, Malik, & Khawaja, 2020). The CO_2 emission from chemical processes is far greater than CO_2 from oil-based chemical processes (J. Chen *et al.*, 2014; Ren & Patel, 2009). According to Mohammad Ehsan Munawer (Munawer, 2018), CO and CO_2 are mainly emitted from the chemical oxidation processes that occur during coal combustion, which significantly contribute to global warming and several health issues including cardiovascular diseases. About 90% of the worldwide CO_2 is from coal, also known as fossil fuel(Ewane & Ewane, 2023). COx gases are climate change contributing factors that lead to flooding and hurricane that negatively affects agriculture and the food chain (Ewane & Ewane, 2023; Gething *et al.*, 2010; Jos G.J. Olivier (PBL) & Marilena Muntean (IES-JRC), 2015). The growth of the plasmodium mosquito significantly depends on the temperature within the environment; therefore, CO_2 emissions may contribute to the increase in malaria, a primary global environmental health concern(Ewane & Ewane, 2023).

Sulfides

Sulfur is released into the environment in gaseous forms during coal combustion, which leads to air, water, and land pollution. The annual sulfides and particulate matter emitted by unregulated coal power plants are twice higher than emissions from factories, trucks, and cars (Delucchi, 2003; Skalska, Miller, & Ledakowicz, 2010). These gases travel hundreds of miles away from power plants to pollute air and water and form H_2SO_4, a significant constituent of acid rain (Likens, Wright, Galloway, & Butler, 1979; Skalska *et al.*, 2010). Aerosols, mist, and smoke combines with SO_2 and may penetrate the lining of the lungs leading to severe lung diseases (Kelsall, Samet, Zeger, & Xu, 1997; Pourgholami, Akhter, Wang, Lu, & Morris, 2005). It affects farm plants and reduces crop yield (Galloway & Whelpdale, 1980; Rajput, DP, & WD, 1977; Winter, Mallepalli, Hellem, & Szydlo, 1994). The oxides of SO_2, NO_2, and limited O_3 generated during fossil fuel combustion produce acid rain upon hydration, fall within the surroundings of industrial locations, and are then transported through rivers and water reserves at far distances. Consuming contaminated food causes severe complications (Foday Jr, Bo, & Xu, 2021). In summary, sulfides negatively impact human health. Coal with low sulfur and ash contents is preferred due to the harmful nature of sulfur.

Nitrogen

The exposure to NO_2 gas emitted from coal pulverization in power plants and burning from our domestic activities aggregates in the air and causes environmental and health problems(Lee, Ha, Lee, Lee, & Kim, 2006; Levy, Moxim, Klonecki, & Kasibhatla, 1999). Pulmonary function is decreased when people are directly exposed to NO_2 gas. Some have been so vulnerable to even lower NO_2 concentrations in the air resulting in asthma, lung malfunction, respiratory failure, long-term pulmonary hypertension in young babies, DNA damage, and cancer(Alexis *et al.*; Arnold, Mittal, Katsuki, & Murad, 1977; Chauhan & Johnston, 2003; Li, Liu, De, & Tao, 2001; Roberts Jr, Polaner, Zapol, & Lang, 1992; Van Amsterdam *et al.*, 2000). Nitrogen acids (HNO_2 and HNO_3) are formed when NO_2 reacts with H_2O damaging agricultural plants, decreasing the rate of photosynthesis and structural buildings, and causing skin burns and skin cancers(A. Singh & Agrawal, 2007). In summary, nitrogen gases and compound affects human health and plants (Skalska *et al.*, 2010).

Particulate Matter

The coal dust and fly ash significantly contribute to forming this component, which causes respiratory problems in children (Brabin *et al.*, 1994; Y. Chen *et al.*, 2004; ClaneyL, 2002; K. A. Miller *et al.*, 2007; Pope III, Ezzati, & Dockery, 2009). The bottom ash found in coal power plants or dumping sites affects aquatic and terrestrial animals (Temple & Sykes, 1992). The coal combustion residue also contaminates soils near ash ponds, decreases soil pH, hinders crop production, and affects the food web (Lokeshappa & Dikshit, 2012). Metals and other constituents in coal enhance the toxicity of particulate matter (Boström *et al.*, 2002; Organization, 2006). The inhalation of PAHs affects DNA molecules, resulting in DNA mutation, child neurodevelopment, reduced IQ, epigenetic effects, reduced child intelligence, cancer, and different cardiovascular diseases (Dragović *et al.*, 2013; Edwards *et al.*, 2010; Jedrychowski *et al.*, 2003; F Perera, Li, Lin, & Tang, 2012; Frederica Perera *et al.*, 2008; F. P. Perera *et al.*, 2009)

The figure below shows how inhaled particles penetrate the lungs. The smaller the particle the deeper they penetrate the lungs. Particulate matter is one main contributor to air-born pollution, and it causes cancers, cardiovascular diseases, and reproductive disorders. Conclusively, particulate matter (PM) from fly ash is another leading source of air pollution that causes various health problems. Hazardous elements in fly ash

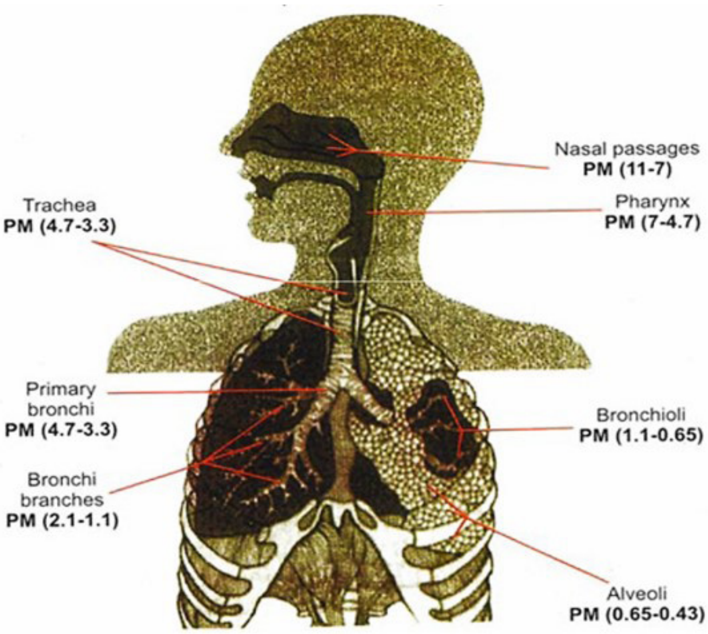

Figure 1: Illustration of how minute particles infiltrate into the lungs(Wilson *et al*., 2009)

The silica fume generated in coal power plants contains toxic elements referred to as heavy metals. The ash constitutes immense amounts of lead, mercury, arsenic, etc., which negatively affect soil and water. They are imperishable chemical elements present in coal gangue. Coal gangue is the leading industrial residue in coal combustion and it is largely produced due to continuous coal combustion. Large stockpiles of coal gangue are in Asian countries such as China and India (Haibin & Zhenling, 2010; Tang *et al*., 2008; Zhao *et al*., 2008).

Lead

Pb is a toxic metallic element found in fly ash, and it contaminates water and air, which travels far and wide areas of coal power plants (Bhangare, Ajmal, Sahu, Pandit, & Puranik, 2011; Fernandez-Turiel, De Carvalho, Cabañas, Querol, & Lopez-Soler, 1994; Goldstein, 1992; Lansdown & Yule, 1986; Mushak & Crocetti, 1988). Exposure to lead damage the kidneys, heart, nervous system, and blood circulation in humans (Foday Jr *et al*., 2021; Naja & Volesky, 2017; Wang *et al*., 2006). Mining, moving vehicles, and burning coal are reported to be the primary sources in an occupationally exposed environment to Pb. Children are more susceptible to Pb exposure than adults (Leggett, 1993; Todd *et al*., 1996).

Mercury

Investigations of coal used in homes for domestic purposes show significant Hg (Naja & Volesky, 2017). Hg is a deadly toxicant in the environment also emitted from fossil fuel combustion and circulates far distances through atmospheric dissemination. Hg is highly unstable in its free state. The bacteria present in water chemically transform Hg to methyl mercury (MeHg) which, when consumed by eating aquatic animals, will conglomerate in their systems and thus affects the function of the brain of the fetus of pregnant women. The increased Hg binding with the thiols of tubulin, a protein that forms the microtubules in the neurons, leads to structural-based pathological modulation, thereby resulting in neuronal migration and other brain deformities in newborns(Lu & Holmgren, 2014; Osman *et al*., 2000; Silva-Adaya, Gonsebatt, & Guevara, 2014).

Arsenic

The release of arsenic poses severe illnesses like lung, heart, skin diseases, etc., and it is known as the third most toxic element. It occurs in different oxidizing states and undergoes various types of chemical reactions to form other products. The human body takes up arsenic trapped in the hair and nails (Dai *et al*., 2012; Kang *et al*., 2011; Liu *et al*., 2007; Tian *et al*., 2013). The amount of trace elements in coal is determined according to grade. Yudovich *et al*. (Yudovich & Ketris, 2005a) in their article stated the average amount of arsenic content around the world for low-rank coal, such as bituminous and lignite coal. Arsenic is released in the form of oxides at lower and higher temperatures (Cui & Chen, 1998; Shpirt, Goryunova, & Zekel, 1998; Yudovich & Ketris, 2005b). Some of the symptoms experienced when arsenic (As) is consumed in food and inhalation are weakness, drowsiness, fatigue, asthma, respiratory diseases, cardiovascular problems, etc. Long-term exposure to arsenic (As) from water and air may lead to anemia, leukemia, leukopenia, and DNA damage that may lead to various cancers like skin and respiratory cancers (Lerman, Ali, & Green, 1980; Okui & Fujiwara, 1986). Conclusively, the release of arsenic from burning coal in power plants leads to severe illnesses, including lung, heart, and skin diseases.

Radioactive Elements in Fly Ash

Radioactive elements, such as uranium, thorium, radium, etc., are also present in fossil fuels and their combustion products. They are released alongside their decay products from the original coal formations in the form of gas or solid. People are exposed to the emission of these radionuclides during fly ash utilization like concrete, stabilization, amelioration, agriculture, etc. Exposure to these will result in severe radiological health consequences like cancer, cataracts, and genetic defects (Amin *et al*., 2013; Gagnaire, Adam-Guillermin, Bouron, & Lestaevel, 2011; Habib *et al*., 2019). Therefore, it is necessary to develop a radiation control program for the exposure of workers and the public in areas where power plants are installed.

Effect on Climate Change

Over the past 20 to 30 years, concerns about the threats and environmental deterioration on the planet have galvanized an international response as scientists, governments, global leaders, policymakers, intergovernmental organizations, and other stakeholders have coalesced to take urgent actions and discussions were centered around developing policy for energy usage within the context of climate (Donaldson & Borm, 1998; Henderson-Sellers *et al*., 1998). Climate change can lead to flooding in coal ash ponds(Ewane & Ewane, 2023). Heavy rains raise the water table that leaks into ponds which may contaminate the groundwater used for agricultural and drinking purposes. Regulations should be developed to control coal ash ponds in coal-producing communities. This will help control coal ash dumps to stop the leaching and subsequent contamination of drinking water. Coal power plants are responsible for managing the environmental impacts that arise from their operations. Heavy penalties should be levied for any health and environmental problems that result from fly ash.

Public Health Impacts

The health problems of fly ash can best be addressed through engineering solutions that efficiently remove particulates from the escaping gases(Yao *et al*., 2015). Heavy metals such as arsenic and molybdenum in fly ash threaten our health and environment if not adequately managed. Inhalation for a very long time causes pneumonitis, allergy, asthma, lung, fibrosis, bronchitis, cancer, and silicosis (Donaldson & Borm, 1998; Murugappan, Manoharan, & Nandhini, 2004; van Maanen *et al*., 1999). The fly ash stored in wet lagoons and dry landfill can infiltrate and contaminate the groundwater if the encage is not correctly lined. People living near the disposal sites of coal ash have a greater risk of cancer and other illnesses from the contaminated drinking water, particularly water contaminated by arsenic which is the most toxic element in coal fly ash. Several studies have been conducted to assess the hazards caused by fly ash on the environment and health (Mehra, Farago, & Banerjee, 1998; Murugappan *et al*., 2004; G. Singh & Vibha, 1999). Exposure to toxic heavy metals in coal fly ash can also affect human development, cause heart and lung problems, lead to stomach ailments, and contribute to premature mortality. Therefore, environmental regulatory agencies in coal-producing countries must categorize fly ash as a dangerous waste. Coal fly ash regulatory agencies should assist the affected communities in enforcing rules and regulations. The low-income earners are affected mainly by the waste disposal sites and often lack the financial and political target to agree with polluters when fighting to seek redress.

Adverse Effects on the Environment

Millions of tons of fly ash leach into water reservoirs and contaminate drinking water. Power plants often use ponds to dispose of their generated solid waste. They should therefore be levied with heavy charges whenever a community accident results from fly ash. The heavy metal elements severely attack the aquatic ecosystem, ultimately affecting fishermen's sustenance. The fishing communities are concerned about the high level of toxic heavy metals found in many water species (fish, prawns, crabs, oysters, etc.).

Figure 2: Photos showing fly ash deposition in a pond

METHODOLOGY

A systematic review was carried out from a sample of 131 articles containing topical-related data. The research question was structurally formulated based on the utilization and environmental health implications of fly ash from previous studies such as (Ahmaruzzaman, 2010; Ghazali *et al.*, 2019; Gollakota, Volli, & Shu, 2019; Tu *et al.*, 2022; Yousuf *et al.*, 2020) which highlighted fly ash utilization and (Dwivedi & Jain, 2014; Finkelman *et al.*, 2021; Gorai & Ash, 2018; Sun *et al.*, 2016; Yousuf *et al.*, 2020) reported their work on the environmental effects of fly ash.

RESULTS AND DISCUSSIONS

According to a statistical report from the data in figure 3, India, China, and the USA are the annual highest fly ash producers, with yearly productions of 112, 100, and 75 million.

India is the top global fly ash producer, followed by China and USA. Their annual statistical utilization is inverse to their production. Among these three countries, the USA utilizes 65% of the fly ash produced, 45% by China, and India 38%. As shown in the data above, Germany is the highest fly ash producer among the European countries while Denmark, Italy, and the Netherlands as the lowest producers (2 million tons per annum each). The three lowest fly ash producers utilize 100% of the fly ash produced, followed by France and Germany, where both equally use 85% of the fly ash production.

The United Kingdom, Australia, and Canada produce 15, 13.1, and 6 million tons annually. Canada uses 75% of the fly ash produced, followed by the UK and Australia, with 50% and 45% utilization, respectively. The Middle East and Africa have an annual production of 32.2 million tons with 10% utilization. In contrast, the Russian Federation and other Asian countries have 26.7 and 16.7 annual outputs with 10% and 18% utilizations of their annual fly ash productions, respectively. Among the three Asian countries (India, China, and Japan) in the above data (figure 3), Japan is the lowest fly ash producer, while India is the highest, followed by China as the second highest. Japan utilizes 96.3% of the fly ash produced compared to India and China. On a global scale analysis, China, India, and the U.S.A. are the leading fly ash producers in the world, according to the data provided in figure 3. The European countries (Netherlands, Italy, Denmark, and Germany) with 100% and 85% and Japan (96.3%) are the highest utilizers of their annual fly ash productions.

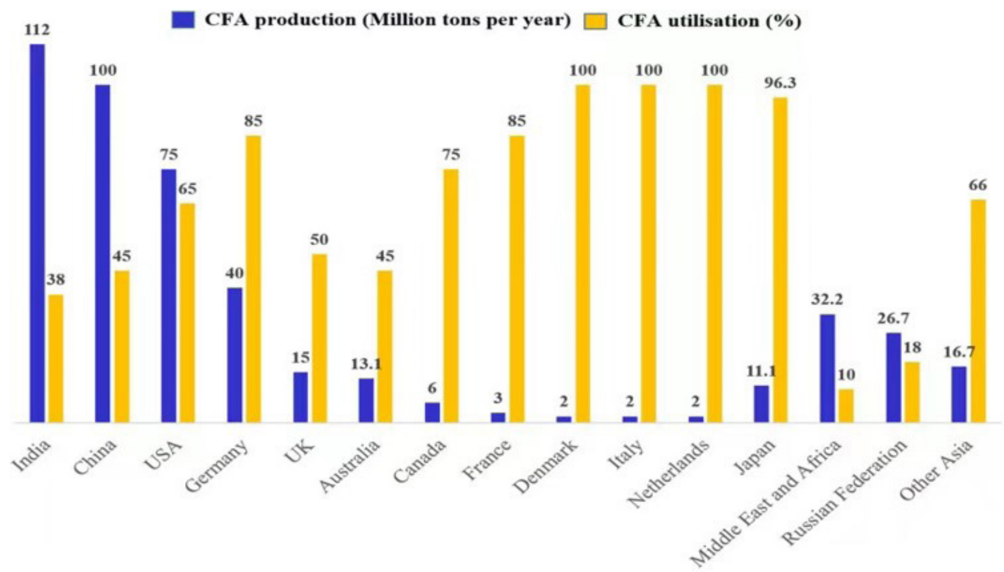

Figure 3: Fly ash production (mtn) and utilization (%) in various countries(Bhatt *et al.*, 2019; Gollakota *et al.*, 2019)

According to the analysis of this review, most countries are unable to utilize all their annual ash productions. Much ash is left unused, particularly in India and China, where it is generated in volumes. This means the remaining ash is probably disposed of or exported to other countries around the globe for utilization in various applications. The global fly ash market for its utilization is briefly summarized below:

From figure 4, the global market size of fly ash in 2021 was USD 12.1 billion. The market growth is projected to exponentially increase to USD 14.33 billion in 2024, USD 15.16 billion in 2025, and USD 16. 90 billion in 2028. The estimated annual growth rate (CAGR) between 2023 to 2028 is 5.8%.

According to a report from Vantage Market Research, Global Fly Ash sales are expanding. The increase in global energy demand is exponentially parallel to the global fly ash market for various construction purposes. It has excellent properties that boost the growth of the fly ash market. China and India are the two countries contributing to the development of the fly ash market due to their increased industrialization and urbanization initiatives to promote sustainable infrastructural projects. They, however, pointed out the following number of factors that are inhibiting the progress of the fly ash market: 1) transportation and storage can be difficult and

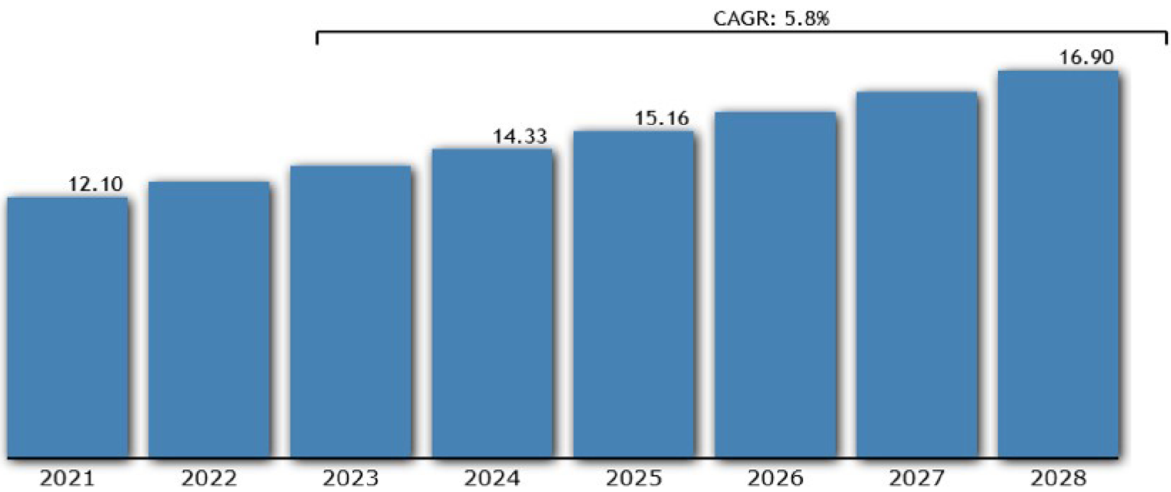

Figure 4: Global fly ash market size and projected growth (Market, 2012)

expensive because the fly ash is a fine powder making it troublesome to handle; 2) Quality variability factor affects fly ash market by making it difficult for the contractors to determine the properties of the ash., and 3) Environmental concern is also a factor because of the potential environmental impact that results in air and water pollution.

The global demand for fly ash is currently overwhelming due to its utilization in multiple applications. This is particularly evidenced in bigger economy nations that have embarked on rapid infrastructural and other development projects. However, there are many health and environmental challenges, primarily from fossil fuel burning, ecological management problems, etc. The dangerous elements encountered during coal and fly ash utilization endangers human health. If not adequately managed, heavy metals and radionuclides circulate into the air or leach into water sources, ultimately jeopardizing human health and crop yield. Also, fly ash utilization should be monitored for radon gas inhalation, particularly in building and construction practices, and potassium, thorium, and radium for soil and crop contamination.

Another environmental concern is the pollution of gases such as COX, NOx, SOx, and particulate matter during coal combustion. COx gases are climate change agents that lead to global warming and flooding. NOx and SOX are acid rain components and affect crop yield and human health. The heavy investment in renewable energy sources to combat the problem of climate change is causing a decline in the conventional production of fly ash due to the closure of several thermal power plants in Europe, the United States, etc. The emergence of alternative new techniques for fly ash production will sustain its utilization and market growth.

CONCLUSION

Although fly ash is utilized for multiple purposes, it however, has so many environmental implications such as emissions (carbon dioxide, carbon monoxide, sulfides, nitrogen, etc) from the burning of coal and hazardous elements (lead, mercury, arsenic, radionuclides, etc) in fly ash which requires adequate management and safe disposal methods.

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