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# Potentially toxic elements in fly ash bricks and associated ecological health risk: An opinionated review

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**Abstract.** Exposure to potentially toxic elements (PTE) from various sources seriously threatens the ecosystem in the modern era. Fly ash produced from coal and solid waste combustion contains a high concentration of PTE. Fly ash is a major by-product of coal-based thermal power plants and municipal solid waste incineration units. Due to the high demand for fly ash reuse due to its unique properties, fly ash is now in demand for manufacturing of various building materials and geo-liner for landfills. Brick is the primary building material used in construction. Fly ash bricks are very popular nowadays due to their low cost and high durability. This study reveals the ecological risk index through the exposure of heavy metals in fly ash reported in various studies. Results indicate extremely high ecological risk mainly due to Cd content in fly ash followed by Hg, As, Cu, and Pb. Fly ash is one of the causative agents for several diseases affecting the nervous system, skin, circulatory system, digestive system, reproductive system, and immune responses in the human body.

## 1. Introduction

Fly ash is produced while using coal in processes or energy generation. Global energy generation is transitioning from non-renewable to renewable, but 25% of total energy comes from coal-based thermal plants [1]. India's 75% of energy comes from coal-fired thermal power plants [2,3]. As per the report, total fly ash generation in India was about 142.07 million tons during 1st half of 2022-2023, among 111.01 million tons of fly ash utilized for different purposes [4]. Fly ash is also produced as a byproduct of municipal solid waste incineration. However, China produces a lot of fly ash through the incineration process. About 780 million tons of fly ash are produced annually worldwide, but only 17-20% of fly ash is utilized. However, statistics indicate India utilizes 38% of produced fly ash, whereas China utilizes 45%, the USA 65%, Germany and France 85%, Canada 75%, and Denmark, Italy, Netherlands utilize 100% of produced fly ash [5]. Fly ash has excellent binding capacity and originated as a waste material, making them excellent for brickmaking. Fly ash bricks are also lightweight, making them valuable from a design perspective [6]. Thus, the utilization of fly ash as a building material, a promising geo-liner for landfills, has drastically increased in the past few years due to the high demand for sustainability practices, especially the campaigns on ‘waste to resources. Like montmorillonite clay mineral, fly ash also proved an effective liner to prevent the leaching of toxic materials from landfills to water tables [7,8].

With emerging fly ash disposal issues, it is used for building materials, including brickmaking. Although fly ash bricks are the best alternative to clay bricks, which save natural resources like earth clay and water, some health consequences are reported for health and safety purposes. In the modern era, fly ash bricks are often used for buildings, road construction, and liners of landfills

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and wells [9-10]. In the past few years, the utilisation of fly ash for brick has increased in almost all countries, including India.

It is also reported that fly ash generated from thermal power plants and other processes, such as solid waste incineration, contains a high concentration of potentially toxic elements (PTEs) [11, 12]. Raw coal itself contains various PTEs, once combustion in high temperature and pressure takes place, PTE remains the same in the fly ash and bottom ash [13]. Few studies have also reported that the concentration of PTE in fly-ash sometimes even increases compared to the PTE content in raw coal [14]. This study aims to assess the ecological risk assessment associated with 890anufacturing and storing fly ash bricks in open spaces and the adverse health impacts on humans exposed to PTE-contained fly ash and fly ash bricks. The study also shed light on the management option to reduce the harmful impacts and improve sustainability by achieving the sustainable development goal (SDG) proposed by the United Nations.

## 2. Material and Method

Secondary data was collected through a random search in the database from 'Google Scholar'. No specific search methods were applied to choose relevant articles for this review article. Major keyword combinations used for this literature review are 'heavy metal in fly ash'; 'potentially toxic elements in fly ash'; 'fly ash generation'; 'fly ash brick'; 'fly ash utilization'; 'fly ash composition'; 'fly ash and waste to resources'; 'heavy metal recovery from fly ash'; 'fly ash management'. A total of 51 relevant articles were included in a compilation of this literature review.

### *2.1. Ecological risk assessment*

Ecological risk assessment was calculated by using the minimum and maximum concentrations of potentially toxic elements in fly ash. The ecological risk assessment is a tool to predict the extent of the ecological effect of harmful elements. Hakanson initially proposed the potential ecological risk index [15]. The method is weighted by multiplying the ratio of the potentially toxic elements to the reference value by the toxicity factor of the same element. It is a set of methods that can well reflect the potential impact of heavy metals on the ecological environment. As fly ash bricks are used and put in open spaces in manufacturing and construction sites for extended periods, exposure to PTEs can be an ecological threat to the flora and fauna. The formulae of ecological risk calculation are as follows-

$$ERI = TR \times Cf$$

$$Cf = \frac{C_{Sample}}{C_{Shale}}$$

$$RI = \sum ERI$$

Where ERI indicates the Ecological risk index, TR denotes the toxicity response coefficient, Cf indicates the contamination. $C_{sample}$ is the potentially toxic element concentration in the sample, and $C_{shale}$ indicates the average shale value of PTEs. The TR for selected potentially toxic elements are following-As=10, Hg=40, Pb=5, Cd=30, Cr=2, Ni=5, Cu=5, and Zn=1. The range of RI indicates the severity of ecological risk. The classification of RI is -RI < 150 represents low ecological risk. 150 ≤ RI < 300 represents moderate ecological risk. 300 ≤ RI < 600 represents a considerable ecological risk, and RI > 600 represents a very high ecological risk.

In the present study, ecological health risk assessment was calculated using the secondary data obtained from the literature. Past studies indicate that the PTE concentration in fly ash was majorly obtained from thermal power plants and that the by-product of municipal solid waste incineration was considered. We considered only the maximum and minimum (excluding 'not detected' or 'below detection limit' values), to get an overview the maximum and minimum ecological risk of fly ash bricks at manufacturing and construction sites.

## 3. Result and Discussion

### *3.1. Fly ash brick composition*

Usually, fly ash bricks constitute a high proportion of fly ash with a small amount of binders. Sometimes, a few proportions of cement, lime, and sand are mixed to increase the tensile strength [16] (Table 1). Due to the pozzolanic nature of lime, it acts as a catalyst once mixed with fly ash. After the reaction with lime, the fly ash accelerator ensures the extent of the reaction. This process is followed by compression, curing, and drying.

#### *3.1.1. Pozzolanic reaction*

When fly ash is mixed with lime and gypsum or cement, the binding material calcium silicon hydrate forms, which looks and acts like a gel [6]. The involvement of lime and gypsum or cement makes this process costly. Still, it is more eco-friendly than clay-based bricks [6]. Researchers are looking for other binding materials to replace cement and lime, making the process more environmentally friendly and economically viable.

#### *3.1.2. Properties of fly ash brick*

Fly ash brick properties depend on its composition. According to Kayali, bricks made with 100% fly ash have a tensile strength about three times higher than normal clay bricks [17]. The compressive strength of fly ash brick was about 43 MPa, and the initial absorption rate was 4.5kg/m$^2$/min with a 10% absorption capacity [17].

#### *3.1.3. Leaching of PTE from fly ash*

The major environmental concern of fly ash usage in brick formation is the high concentration of potentially toxic elements in it. The study also suggested the PTE concentration differs with the type of coal combustion or the type of waste gets incinerated. Lignite and bituminous coal produce comparatively higher contaminated fly -ash, while anthracite coal combustion produces less PTE concentrated fly ash. In India, the majority of coal used in thermal power plants is lignite and bituminous; thus, the PTE concentration in fly ash is found to be higher than that in countries that are highly dependent on anthracite coal-based power plants.

**Table 1.** Composition of fly ash bricks.

| Material | Proportion |
|---|---|
| Fly ash | 57-65% |
| Sand/stone dust | 18-27% |
| Gypsum | 5% |
| Sludge Lime | 15% to 22% |
| Cement | 8-12% |

### *3.2. Concentration of PTEs in fly ash*

Table 2 indicates the PTEs concentration in fly ash obtained from different thermal power plants and solid waste incineration units across the globe. The PTE content in the fly ash can pose ecological hazards, particularly when stored outside (Fig.1). PTEs are known to cause environmental and health toxicity. Very high arsenic concentration was reported in the bottom ash and fly ash obtained from the combustion of lignite [18]. Another study by Gopinathan et al.,

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2022 suggested extremely high concentrations of Co, Pb, Cu, Cr, Ni, and Zn were in the fly ash of the coal mine area in India [19]. Thus, the PTE concentration varies with the type of parent material that gets combusted. Basically, fly ash is generated in countries like India, where over 86.35% of Megawatt of energy is generated from coal-based thermal power plants [3,20,21]. Indian thermal power plants are based on the bituminous and lignite coal, which comparatively contains high PTEs. Pb, particularly in the $Pb^{2+}$ form, can cause impairment in the neurological system and impact the brain. Long-term or chronic exposure can lead to memory loss, fatigue, dementia, and learning disabilities in children. Hg, though not that toxic in elemental form, but its organic derivative, methyl mercury, can cause bioaccumulation in the fat-rich portion of the human body. Brain cells are nerves with high concentrations of lipids, which form an insulating lining of the neurons, also known as the myelin sheath. Methyl mercury accumulates in these sections of the body, causing neuron toxicity. Over-exposure to hg can lead to memory loss and uncoordinated movement as the metal impacts the brain's motor cortex and tremors. Positively charged metal ions impart cellular toxicity by disrupting the enzymatic functioning of the cells. Chromium, particularly in the hexavalent form, can also cause genotoxicity, resulting in carcinogenesis. Similarly, Cd, being in the same periodic group as Zn, can replace the metal in cells, resulting in higher bioaccumulation into the cells [22].

**Figure 1.** Outdoor storage of Fly ash bricks meant for building construction

**Table 2.** Potentially toxic elements (mg/kg) in fly ash, where ND indicates 'not detected', and NR indicates 'not reported'

| References | Remarks | As | Co | Cu | Hg | Pb | Cd | Cr | Mn | Ni | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [13] | Fly ash samples were analyzed from Four thermal power plants in China | 4.59 - 15.0 | NR | NR | 0.064-0.977 | ND-41.6 | ND-0.98 | 6.2 -88.6 | NR | 3-53 | NR |
| [50] | Fly-ash samples | NR | 8-18 | 56-83 | NR | 20-56 | NR | 87-103 | 47-139 | 28-63 | 60-124 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | from three power plants in North India | | | | | | | | | | |
| [19] | A total of 20 fly ash samples were collected from various mining areas of Talcher Coalfield, India. | NR | 69.6-113 | 168.9-248.4 | NR | 151.2-309 | ND-3.6 | 260.4-387.9 | NR | 86.9-162.2 | 116.9-418.7 |
| [51] | PTE content in Fly ash produced by Municipal solid waste incineration in China | 3.8-42 | NR | 43-913 | 1.5-2.9 | 65-312 | 0.80-17.4 | 25-303 | NR | 6.0-115 | 282-2630 |
| [52] | PTE content in the fly-ash generated from coal-fired thermal power plant, Parichha, Jhansi, India | NR | NR | NR | NR | 34.809 | NR | 64.772 | 286.205 | 51.609 | NR |
| [14] | Potentially toxic elements in fly ash obtained from bituminous coal burning | ND | 31-43 | 65-95 | NR | 20-70 | ND | 139-254 | 325-393 | 100-135 | 49-85 |
| [18] | PTE content in bottom ash and fly ash of Lignite/hard rock | 7.6–135 | 0.03–2.0 | 4.4–66 | NR | NR | 0.2–74 | 4.0–92 | NR | 16–79 | 19–155 |

### *3.3. Ecological risk assessment*

The ecological health risk obtained through maximum and minimum concentrations of PTE is tabulated in Table 3. *It indicates* that the maximum ecological risk is exceptionally high as it is more than 2.5 times higher than the maximum ecological risk index category (> 600 ERI). Higher ecological risk indicates a threat to the ecosystem, which could be contaminated with PTEs. Which directly and indirectly affects the human population and all flora and fauna in nearby areas. A very high ecological risk index can be seen through Cd, followed by Hg, As, Cu, and Pb in fly ash (Table 3). Wang et al. also reported that the maximum ecological risk posed by Cd exposure to PTE by fly ash [13]. While not a direct health impact on humans, the environmental consequences of fly ash pollution can indirectly affect human health through contaminated water sources, soil, and food chains. Storage and disposal of fly ash brick can have a negative impact on plants and affect soil fertility [23].

**Table 3.** Ecological Risk Index (ERI) calculated through maximum and minimum PTE concentrations of various fly ash

| | As | Cd | Cr | Cu | Ni | Pb | Zn | Hg | Mn | Co | ERI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ERI max | 69 | 1160 | 6 | 68 | 8 | 52 | 18 | 193 | 0.3 | 8 | 1582 |
| ERI Min | 2 | 13 | 0.1 | 0.3 | 0.1 | 3.3 | 0.1 | 4.3 | 0.04 | 0.00 | 24 |

### *3.4. Major health issues from Fly ash*

#### *3.4.1. Respiratory Issues*

Fly ash particles are extremely fine, often smaller than 2.5 micrometres ($PM_{2.5}$), which allows them to penetrate deep into the respiratory system [24, 25]. Inhalation of fly ash can lead to respiratory problems such as asthma, bronchitis, and aggravated symptoms in individuals with pre-existing respiratory conditions [26]. Sometimes, PTE present in fly ash is also exposed to humans through ingestion and causes potential health issues such as tumours and pulmonary cancers [29, 30].

#### *3.4.2. Neurological Effects*

Potentially toxic elements such as Pb, Cd, As, and Hg, found in fly ash, can have neurotoxic effects and brain cancer [31,32]. Prolonged exposure to these substances may impair cognitive function and contribute to neurological disorders. Once metallic ion enters living cells, they interfere with cellular metabolic activities to produce ROS, which ultimately affects cell cycling progression [33]. Sometimes, these free radicals (ROS) can be the reason for a few major neurological disorders, such as Parkinson's [34-36].

#### *3.4.3. Skin Irritation*

Direct contact with fly ash can cause skin irritation and dermatitis in sensitive individuals. It is reported that heavy metal exposure through fly ash generated through municipal solid waste incineration poses human health risks, especially through inhalation and dermal contact [35]. A review study indicated that skin disorder is a major health issue among workers and those near cement industries [24,38,39]. Fly ash usage in brick and cement production is very common nowadays, which indicates its alarming health hazard if fly ash is not characterized earlier for PTE concentration.

#### *3.4.4. Reproductive Health*

Exposure to certain components of fly ash, such as heavy metals, has been linked to reproductive issues, including reduced fertility and developmental abnormalities in fetuses. It is proven that the reproductive health of fish is negatively impacted by exposure to PTE from coal ash [38]. Studies also suggested that exposure to fly ash can cause birth defects and abnormalities in fetuses due to chronic exposure to PTEs through ash particles [39]. Another study also suggested that the endocrine system gets impacted through exposure to fly ash, which ultimately creates imbalances in reproductive hormones [40].

*3.4.5. Immune System Impairment*
Chronic exposure to fly ash may weaken the immune system, making individuals more susceptible to infections and illnesses. Fine particles of fly ash through manufacturing and disposal processes have proven hazardous for the immune health of children [41]. PTEs such as Pb, Cd and Hg exposure through fly ash bricks can cause immune system impairment, mostly in infants, children, and elderly age groups. Sometimes chronic exposure of these PTE is responsible for cancer progression [42-45].

Potentially toxic elements in fly ash can have adverse effects on human health. The fly ash brick containing PTEs can pose different health hazards to humans exposed to it from the manufacturing unit to the disposal units. PTEs, mainly Cr, Mn, Ba, Rb, Be, Co, Cu, Ni, As, Cd, Pb, Zn, Se, and Hg, are major PTEs reported in the fly ash [44]. Recovery and removal of PTE from the fly ash before reusing it for brick-making can be a management recommendation for reducing health impacts [47]. Recent studies suggested that recovery of PTEs is possible through the adsorption and leaching processes [48,49]. An enclosed environment for manufacturing and storage can also increase the scope of reutilization of fly ash for a better future to achieve a sustainable environment. Thus, the UN sustainable development goals (SDG) can be achieved. SDG 3 -Good health and well-being, SDG 11-Sustainable cities and communities, and SDG 12- responsible consumption and production.

## 4. Conclusion and recommendation

This study concludes that untreated fly ash can pose ecological and human health hazards if used for any building and construction work. It is suggested that manufacturing and storing fly ash-based building materials, primarily fly ash bricks, must be kept in an enclosed environment instead of in an open space for extended periods. Putting fly ash in the open can lead to the leaching of heavy metal eighter due to areolar erosion or water. Fly ash can cause respiratory, neurological, reproductive, and other toxic responses in humans, and heavy metals can bioaccumulate in the food chain, causing ecotoxicity.

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