



SPECIATION OF INDIAN COAL AND FLY ASH IN THERMAL POWER STATION AND IT'S IMPACT ON HUMAN HEALTH AND ENVIRONMENTS

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ABSTRACT

Thermal power plants that use coal are among India's worst pollutants. These plants' coal combustion emits hazardous pollutants such as carbon monoxide, sulfur oxides, nitrogen oxides, chlorofluorocarbons, fly ash, and suspended particulate matter. Increased greenhouse gas emissions and atmospheric harm are produced by the inefficient combustion of Indian coal, which contains a high ash content. Inadequate management of fly ash, a microscopic particle consequence of coal combustion, poses serious dangers to human and environmental safety. Cancer, chronic bronchitis, skin irritation, and respiratory diseases can all come from improper disposal or discharge into the air, water, or land. Additionally, the presence of lead, mercury, and arsenic in fly ash has a deleterious influence on biodiversity and ecosystems. Despite objections, fly ash is progressively replacing cement in construction projects. To mention a few, concrete's pozzolanic properties improve its workability, durability, chemical resistance, and hydration temperature. Despite its low initial strength, fly-ash concrete beats normal concrete in the long run. Furthermore, it reduces creep under early-age pressures, hence improving structural integrity. Improving combustion, desulfurizing flue gases, and managing ash can all help to reduce coal and fly ash. Engineers and scientists are contemplating using fly ash into bricks, road construction, mine fills, and agriculture to reduce waste and improve sustainability.

Keywords: Fly Ash, Indian Coal, Thermal, Power, Station, Human, Health, Environments

INTRODUCTION

Coal is India's sole fossil fuel. As a fuel for thermal power plants that generate electricity and heat energy, it is widely employed. India has been increasing its electricity producing capacity for decades to accommodate population growth. Around 70% of the world's electricity originates from coal-fired thermal power plants. High-grade coal is used in metalworking. Thus, thermal power plants use low-grade coal. Thermal power plants' coal-fired heat generation is the most hazardous to persons and the environment. Most thermal power plants that burn coal produce CO₂, SO_x, NO_x, and CFC particles, including fly ash and suspended particulate matter. Inefficient burning and excessive coal ash concentration generate greenhouse gas emissions from India. (R. Meena, 2022) Coal-fired thermal power facilities in India emit 12.21 million tonnes of fly ash annually. More than a third is discharged into the atmosphere, while the remainder is disposed of on land or in water. As coal usage rises, land and water contamination will result. Fly ash water interacts directly with water, affecting scale structure (Jaworek, A., 2021). Coal combustion residues are coal combustion byproducts. It contains boiler slag, bottom ash, fly ash, fluidised bed combustion ash, and other solid small particles. Indian coal-fired thermal power stations create 105 MT of CCRs, which harm the environment. Thermal power stations currently dry fly ash from all semi-wet ash ponds using ESPs under dry conditions. No Indian thermal power station routinely collects dry ash. Bottom and fly ash are often dumped into the ash pond or lagoon. This affects all three realms. (G. Wang 2021) Although Indian coal and

fly ash have been extensively researched, many critical details remain unclear. The absence of region-specific data on coal and fly ash chemical speciation is a significant disadvantage. The majority of present study concentrates on Singrauli, Talcher, and Korba, leaving other locations unexplored, despite the fact that specific geological occurrences may influence elemental composition. The majority of current research on heavy metal exposure and mobility in the environment focuses on determining total concentrations of these contaminants rather than assessing their bioavailability or chemical binding forms.

Additionally, there is a clear dearth of long-term epidemiological studies that link exposure to fly ash over extended periods of time to the health effects experienced by local communities. (M. Basu, 2023) The bulk of health effect statistics rely on short-term or indirect evaluations, which limits our ability to draw definitive conclusions about dangers. Even though fly ash contains micro and ultrafine particles, very little is known regarding their formation, transportation, or potential health effects, especially in India. Research on the rate of recycled fly ash leaching from construction materials in India is limited. Despite the material's economic importance, research into extracting REEs from Indian fly ash using sustainable extraction techniques is still in its early phases.

Characteristics and usage of coal and fly ash

Burning coal to produce steam from water is the primary usage of coal in power plants. Although the exact percentage varies by region, coal accounts for around 30% of the world's power mix. In addition to several other pollutants, fly ash is the most prevalent solid waste product of coal combustion processes. The byproduct of burning coal in boilers is fly ash. Bag filters or electrostatic precipitators separate the tiny ash particles carried by the flue gases. On the other hand, according to Ahmaruzzaman (2010), about 30% of the fly ash that is generated goes unused. This means that methods for recovering value from fly ash must be ongoingly improved. (A. Bhatti, 2010) Possible uses for it are mentioned in the article. Ash's chemical and physical qualities make it valuable in many manufacturing processes.

Burning pulverised coal produces fly ash, which may include significant cenospheres. The boiler melts ash into spherical particles at temperatures above 1100 °C. They contain flue gases, principally nitrogen and carbon dioxide. Cenospheres, which are primarily Al_2O_3 and SiO_2 , can be used as polymer composite fillers, according to Vassiliev (2007). The created materials are stronger than those without filler. Cenospheres reduce heat conductivity and increase thermal stability. , M. Wang, (2024) Consequently, they find work making insulation and building supplies. Also found in fly ash, ranging from 1-8%, is unburned carbon. Its presence may be helpful while absorbing harmful substances. Typical uses of fly ash from coal combustion include zeolite synthesis, cenosphere separation, water purification, and agriculture, among others. The following study presents the characteristics of fly ash and its typical applications (S.S. Alterary, 2021). Among the many creative uses for fly ash mentioned in this article are the production of reinforced polyurethane materials using microspheres made of fly ash, the modification of polymers using fly ash as an eco-friendly filler, and new applications for the fly ash silanization process. (Yao, Z.T., 2015).

Figures 1 and 2 show that more projects are using fly ash (FA) instead of cement. Fly ash greatly improves concrete slide resistance. Concrete with fly ash has lower early strength but higher late strength than ordinary concrete. Early-age loads reduce concrete creep. Fly ash accelerates concrete slip. Fly ash decreased concrete crawling, according to F. Xi and S.J. Davis (2016). Fly ash, a common mineral addition, has been studied for its influence on concrete creep. Fly ash at 12 or 30% decreased concrete creep shrinkage compared to cement alone (P.J.M. Monteiro, 2017). Several research have explored fly-ash-regenerated concrete creep. Completely recycled concrete creeps more than conventional concrete (S.A. Miller's, 2020) . According to Chindaprasirt (2017). As concrete strength improves, creep resistance decreases because limestone contains more tricalcium aluminate (Hemalatha and Dwivedi, 2017). This study reviews fly ash in concrete articles. The literature and advances have been thoroughly reviewed (R. Siddique, 2016). Fly ash is a cost-effective, environmentally friendly, and property-enhancing construction material.

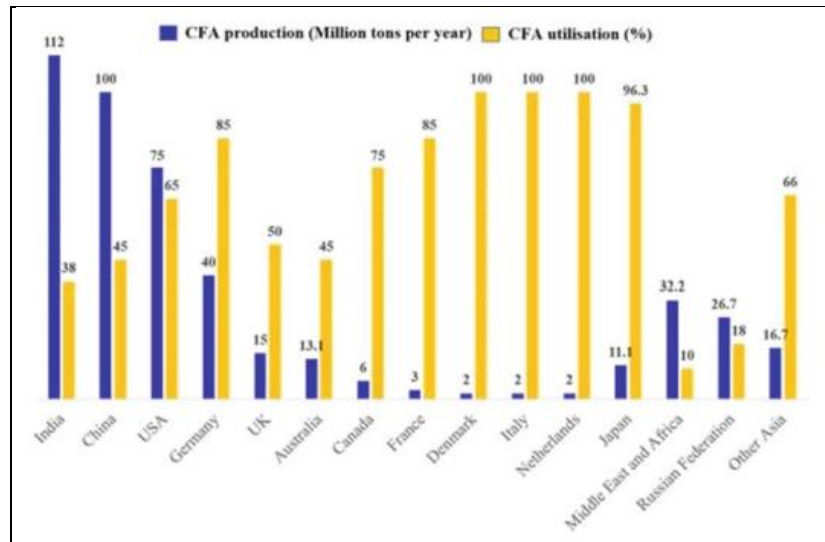


Fig. 1 Manufacturing and use of fly ash worldwide(R. Siddique, 2016)

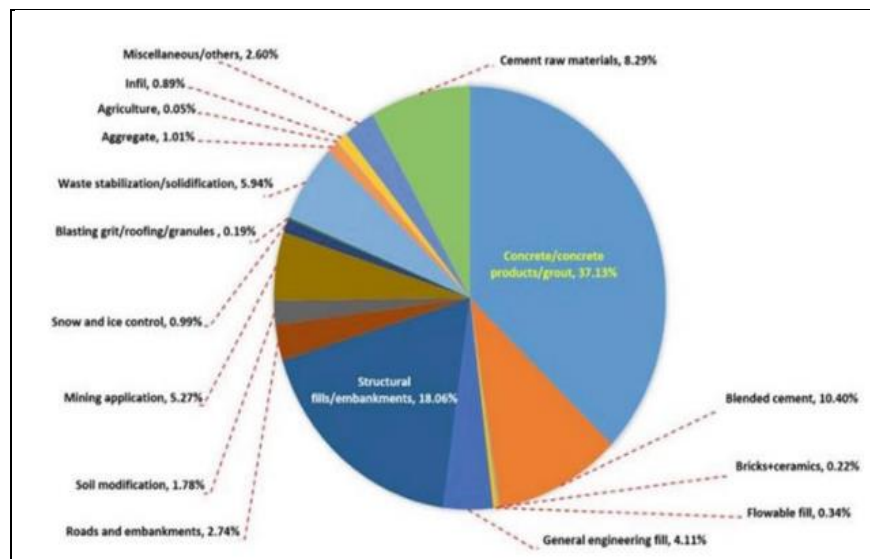


Fig. 2 Possible proportion of fly ash used (H. Zhao, 2019).

The Use of Fly Ash in Geopolymer Is Essential

This study examined FAA-GPCC concrete due of its environmental impact. The material's strength was equivalent to OPC concrete in numerous FAA-GPCC tests. FAA-GPCC technology may provide economical and environmental benefits. If FAA-GPCC is to be the best long-term therapy, its effects on GPCC's long-term aspects must be considered. Numerous papers have examined FA applications and how they influence GPCC system technology. Another component of this study details FA applications. Pulverised coal combustion produces fly ash (H. Zhao, 2019). The result of burning coal. The boiler contains molten mineral waste after pulverised coal burns. After flue gas is collected and cooled in boiler tubes, waste solidifies into ash. The larger "bottom ash" or "slag" particles are driven to the combustion chamber bottom depending on their size. FA is recovered from flue gas by evaporators and filter baghouses before exhaustion. Although unburned colloidal particles don't burn, they alter fuel qualities. The mineral composition of FA-producing coal varies by kind. Important considerations include coal availability, pulverisation level, combustion conditions, ash collection and processing, and

disposal (Y.H.M. Amran, 2017). FA production varies each power plant since each plant is unique. Plants create different FAs depending on fire circumstances.

In addition to a number of inorganic minerals, coal is a complex heterogeneous substance mostly made up of carbon, hydrogen, oxygen, nitrogen, and sulphur (Spears, 2012). According to Ward (2002), coal contains an organic component of around 70% carbon by weight, with the inorganic portion made up of aluminosilicates, carbonates, sulphides, and trace metals. The inorganic minerals that remain after burning coal are changed into fly ash, a fine particulate residue that retains the coal's original mineral composition but undergoes changes owing to high-temperature reactions (Vassilev and Vassileva, 2007). Fly ash often contains silicon dioxide (SiO_2), aluminum oxide (AlO_3), iron oxide (FeO_3), and calcium oxide (CaO), as well as trace amounts of magnesium, potassium, sodium, and trace metals such as arsenic, lead, and mercury (Querol et al., 2001). The composition of fly ash varies depending on the kind of coal used (lignite, bituminous, or sub-bituminous) and combustion circumstances (Izquierdo & Querol, 2012). Fly ash is useful in environmental and construction contexts because it contains amorphous aluminosilicate glass as well as crystalline phases such as magnetite, quartz, and mullite. (Blissett & Rowson, 2012). Because of the importance of coal and fly ash to industry and the environment, extensive study has been conducted on their elemental and mineralogical compositions. Coal is largely made up of inorganic components such as macerals and mineral matter, which might include clay minerals, kaolinite, quartz, pyrite, and calcite. Coal burning concentrates these minerals, transforming them into fly ash with a glassy or crystalline appearance. Vassiliev et al. (2010) found that fly ash mostly consists of SiO_2 , AlO_3 , FeO_3 , and CaO oxides, with trace amounts of heavy metals, rare earth elements (REEs), and minor oxides such as MgO , KO , NaO , and TiO_2 . Fly ash includes hazardous components such as arsenic, selenium, and mercury, raising worries about its leaching and environmental effects (Zhang et al., 2008). Combustion alters mineralogical properties, such as the creation of mullite and amorphous aluminosilicate glass, which are temperature and composition dependent processes that begin with the parent coal, according to Matjie et al. (2005). Although lignite-based ash is richer in calcium and sulphur compounds, fly ash derived from bituminous coal typically has higher concentrations of alumina and iron oxides (Goodarzi, 2006). These compositional differences are important for determining whether fly ash is suitable for applications such as zeolite synthesis, cement production, and soil amelioration (Adriano et al., 1980; Vassilev & Vassileva, 2007).

OBJECTIVES OF THE STUDY

1. To study on Characteristics and usage of coal and fly ash
2. To study on Coal and fly ash speciation
3. To study on Health Risk Problems Associated With Increasing Fly Ash and coal combustion

METHOD

The study design by Reviewing qualitative literature. The data was derived from scholarly articles, government reports, and environmental bulletins that were published somewhere between 2018 and 2023. This study focuses on the elemental and mineralogical speciation of fly ash and coal collected from thermal facilities in India. Risk assessments for soil, air, and water contamination, as well as toxicological examinations into fly ash exposure. Production and Utilisation of CFA in India This details the main oxides, trace elements, and mineral forms of fly ash and Indian coal that are often found in thermal power plants, based on studies conducted in Indian coalfields. The current state of affairs regarding fly ash disposal and reuse regulations, policies, and practices may only alleviate the environmental impact of its overproduction; yet, contamination will still happen. To develop effective containment, control, mitigation, and preventive strategies, it is important to understand the intricate interactions between CFA and live species. Due to CFA's physicochemical properties, this article discusses human health epidemiological studies, its toxicological effects on various organisms (from bacteria to mammals), and its molecular and cellular toxicological mechanisms. We want more public health research on coal fly ash and increased awareness of its environmental risks.

Secondary sources were located using databases such as ScienceDirect, Scopus, PubMed, and ResearchGate. Notable writers include Finkelman (2017), Zhang et al. (2021), Goodarzi (2022), and Vassilev et al. (2018).

India's Thermal Power Plant Situation

In 2021 and 2022, thermal power plants in India produced 133 MTs of CFA from coal and lignite combustion. About 75% of the nation's power comes from these facilities. The 2021–2022 half-yearly data suggest that no additional TPPs will generate power beyond 2027. According to Singh, Deborah (2022) and the NEP (2021), India is anticipated to have 50,025

MW of coal-fired thermal power plants. This is excellent news for India's energy and economy. Thus, CB-TPPs need a dependable coal supply to generate energy. Q. Xiahou 2022

CFA output may exceed 1000 MT by 2031–2032. Despite research and advancements, nearly half of the CFA is still wasted each year. The continued dumping of residual CFA pollutes air, water, and land, according to B.N. Adeleye (2021). Official CB-TPP figures showed an annual growth, making the situation unsustainable. A. Edianto (2020) Super TPPs will offer numerous benefits, but the government and residents will worry about pollution. (O.Marinin , 2016)

India's Production and Use of CFA

Between 1993 and 1994, coal output averaged 40 MTs, with CFA utilisation about 3%, or 1 MT. In contrast, CFA consumption rose 60.97 percent from 6.64 MTs in 1996–1997 to 107.77 MTs in 2015–2016. The future of thermal power plants may be better predicted by looking at total coal consumption, CFA production, and CFA utilisation. India's huge economy makes it likely to control the world. Coal combustion creates energy and harms the environment. Many methods have been devised for their efficient treatment and disposal. Many will remain adamant about the CFA's management. Advances in CFA-based approaches and objects changed hazardous waste categorisation to "useful and saleable asset". Indian state-owned companies, private groups, and government agencies like the National Thermal Power Corporation developed coal-fired thermal power plants (TPPs). India has a huge coal supply for thermal power plants (TPPs). Multiple government agencies monitor TPP installation, operation, life cycle, CO₂ emissions, CFA generation, and consumption. All thermal power plants submit data to the Central Electrical Authority of India (CEA), which publishes an annual report in December and a half-yearly report in June. Based on CEA reports from 2010–2011 to 2021–2022, Table 1 shows data collecting outcomes.

Table 1. Production and use of CFAs over the 1996–1997 to 2020–2022 timeframe (CEA reports December 2021/July 2022). (Nandi, M., 2022).

S. No	Year	CFA Production (Million Tonnes)	CFA Utilization (Million Tonnes)	Percentage (%)
1	1996–1997	98.57	37.49	38.04
2	1997–1998	98.97	45.22	45.69
3	1998–1999	108.15	55.01	50.86
4	1999–2000	82.81	15.57	18.80
5	2000–2001	91.65	20.79	22.68
6	2001–2002	96.28	28.29	29.39
7	2002–2003	68.88	6.64	9.63
8	2003–2004	78.06	8.43	10.80
9	2004–2005	172.87	99.62	57.63
10	2005–2006	184.14	102.54	55.69
11	2006–2007	176.74	107.77	60.97
12	2007–2008	131.09	73.13	55.79
13	2008–2009	145.41	85.05	58.48
14	2009–2010	163.56	100.37	61.37
15	2010–2011	78.99	9.22	11.68
16	2011–2012	74.03	8.91	12.03
17	2012–2013	86.29	13.54	15.70
18	2013–2014	116.94	61.98	53.00
19	2014–2015	116.69	66.64	57.11
20	2015–2016	123.54	77.33	62.60
21	2016–2017	226.14	189.01	77.59
22	2017–2018	232.56	214.91	83.28
23	2018–2019	270.82	259.86	92.41
24	2019–2020	169.25	107.1	63.28

25	2020–2021	196.44	131.87	67.28
26	2021–2022	217.04	168.4	67.13
27	2022–2023	-	-	

According to the figures in Table 1 (CEA, 2022), the development and usage of CFAs showed a constant expansion from 1996–1997 to 2021–2022. The increased production of CFA is supposedly caused by the launch of new super TPPs. It is possible that the increase in CFA usage in 2022 was caused by stringent government norms, rules, information, legislation, and technological improvements. Higher adoption rates of CFA could be attributable, in large part, to the tools that make it easier to assess its overall qualities. Park (2022). The usage of CFAs increased significantly from 1996–1997 to 2021–2022, as seen in Table 1. Only 9.63% of CFA were used between 1996 and 1997; following that, the different forms' usage was progressively increased. (Nandi, M., 2022). The CFA utilisation rate, however, rose to 81.65 percent in 2021 and 2022. According to these figures, CFA is expected to be used more often in India soon. (Yuan, Q., year 2021) Technological progress, government initiatives, laws, and public awareness will ensure that hazardous waste does not contribute significantly to pollution in the foreseeable future. In 2022, C. Hasse The government predicts that CFA production would range from 240 to 300 MTs from 2020 to 2025. (Y. Chen 2022). Coal and lignite thermal power plants in India accounted for 83% of the 226 MTs of CFA produced using these fuels in the 2020 fiscal year. An analysis of CFA utilisation rates from 2015 to 2021 (the first half of the fiscal year) revealed an upward trend. 3, which spans the years 2015–2021, shows the CFA production and consumption in India. The data shown only include the fly ash generation and usage for the first half of 2021. (Z. Wei 2021),

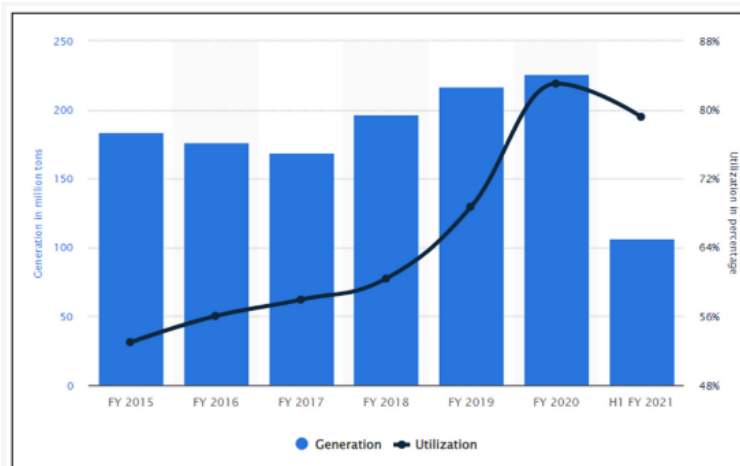


Figure 3. Production and use of coal fly ash during the previous seven years, from 2015 to 2021 (Nandi, M., 2022).
Alternative materials for the production of electricity

The most common types of coal used in industrial and power generation are bituminous and sub-bituminous coals due to their abundant global availability and relatively high energy content (Speight, 2013). In countries like India and Germany, where higher-grade coal is scarce, lignite is used often even though it has a lower calorific value (Goodarzi, 2006). In an attempt to reduce emissions of greenhouse gases, coal is being co-fired or substituted with other fuels such as natural gas, biomass, petroleum coke and municipal solid waste (MSW) more often, even though coal is still the most used energy source (Baxter, 2005). Cofiring biomass with coal reduces SO_2 and NO_x emissions while maintaining energy efficiency; this was shown by Tillman (2000). To aid in the removal of sulphur during fluidised bed combustion, coal combustion systems often use sorbents such as dolomite and limestone (Anthony & Granatstein, 2001). Following combustion, the flue gas stream is frequently treated with ammonia, urea, and activated carbon to minimize pollutants, notably nitrogen oxides (NO_x) and mercury (Senior et al. 2000). According to Demirbaş (2005), the optimization of present coal infrastructure and the coupling of renewable energy sources with waste fuels are being pursued as part of a global movement toward decarbonization. Despite all of these advancements, coal remains an important part of many governments' energy strategies. Developing countries confront distinct hurdles in implementing rapid energy upgrades due to insufficient infrastructure and financial resources (IEA, 2022).

Petroleum and natural gas

Refinery investment decisions depend on refining, reservoir basin development, and petroleum product demand. India has 0.4% of world hydrocarbon reserves. India's oil is mostly in Assam, Mumbai, Cambay, and Krishna-Godavari basins. After independence, the government built 13 refineries to handle 604 million metric tonnes of crude oil. According to Sengupta (1993), natural gas should be properly studied like crude oil. India's crude oil output meets barely 47% of domestic needs in 1993–1994. India has 733.7 million metric tonnes of recoverable crude oil in 2001. India bought \$12.6 billion in crude oil in 2001 and 2002 to suit local demand. The country has 749.65 billion cubic meters of natural gas in 2001. At one point, Indian electrical utilities utilised petroleum fuels. Singh R. (2021) India produced 102.2 million metric tonnes of petroleum in 2001–2002, up from 17.11 million in 1970–71. The eleventh-year plan forecast 147 million tonnes of petroleum product use and 46 billion cubic meters of natural gas demand, a 6% GDP increase. India's oil reserves may last 20–25 years at present consumption. In 2003–2004, 31.96 billion m³ of natural gas was produced. Nearly 75% of Indian cooking fuel is LPG. Clearly, 22 kilogramme of LPG is used annually for cooking. (Chu S., 2021)

Non-conventional resources

Bhide and Monroy (2015) discuss energy poverty in India and renewable energy's long-term remedies. In order to attract investors and become a global leader in energy growth, India has raised its non-conventional energy capacity to above 175 GW by 2022. Government initiatives aim to keep carbon dioxide levels under control. (Singh AK., 2023)

Solar energy

Daily solar radiation hits Earth at high levels, influencing a wide range of events (both good and negative) that have been the subject of much study. The energy that people get from the sun might be enough to power their daily lives. Clear, sunny weather is present for 250–300 days a year in much of India. Past research by Palit (2020). Solar energy reaches India at a rate of more than 5,000 trillion kWh per year. Approximately 1016 W of solar energy reaches Earth's surface. To fulfil all of humanity's demands, the globe would require around 1013 W of power. So, solar power provides us with almost 103 times the amount of electricity we use. Even if we can just use 5% of the energy mentioned, it will produce more than 50 times as much energy as the earth needs. (Chattopadhyay D., 2022,)

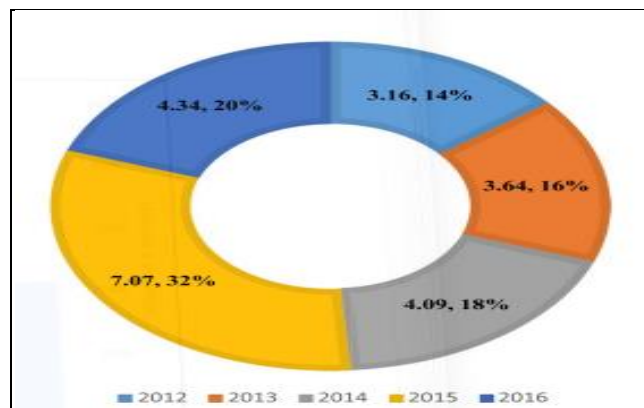


Figure 4. Installed capacity for solar power generating as of December 31, 2016 (in GW, percentage yearly) (Y. Qin , 2023)

Wind energy

Power consumption is increasing due to the fast population and economic growth in India. Wind power may be a game-changer in this area due to its cheap cost and minimal impact on greenhouse gas emissions. (Y. Qin , 2023) Using a GIS, wind maps are generated at an 80-meter turbine hub height to determine the offshore wind potential and evaluate the feasibility of wind power. The study found an average wind speed of 9.7–13.4 m/s and wind power density of 1048.7–1632.5 W/m². India has the fourth-most wind power capacity, behind the US, Germany, and China. India's renewable energy potential surpasses 900 GW. In order, it has 102, 750, 25, 20, and 3 GW of solar, wind, biofuel, minor hydro, and

other resources. New wind power plants have been built across the country. Seven Indian states have 1,000 MW wind power plants. Wind resources are most concentrated on non-farming land in Gujarat and Rajasthan. India's offshore wind energy potential is estimated at 214–304 MW. Wind energy accounts for 65.2%, or 23.76 GW, of India's renewable energy capacity and is expected to reach 60 GW by 2020. (Y. Qin, 2021).

Biomass/biogas energy

The term "biomass" refers to any organic substance that is not directly from an animal or plant source; it is a renewable energy source. The biomass consisted of a wide variety of organic matter, including animal and human waste, food and wood scraps, agricultural crop residue, and wood and wood processing byproducts. Both commercial and household energy production rely heavily on this form of energy. This is why, despite the fact that forests cover 24% of India's territory, the agricultural sector remains vital to the country's economy. (Dehghani, Madvar, 2021). Biomass accounts for over 25% of global energy production, with certain countries seeing that number rise to 90%. Biomass accounts for over 12.83% of India's overall power generation. Burning the materials in a combustion process or transforming them into biofuel (in liquid or gaseous form) are the two main methods for producing energy from biomass. Among the most significant issues with this energy source are the deforestation and air pollution caused by biomass combustion. To reduce air pollution and forest loss, it is preferable to implement programs that use biofuel, especially biogas, in place of burning biomass directly. (Govindaraju, 2019 for VGRC)

Table 2. India's installed capacity for biogas-fed electricity generation (Dehghani, Madvar, 2021)

Year	Installed capacity (MW)
2008–2009	3095
2009–2010	3565
2010–2011	4013
2011–2012	4165
2012–2013	4938
2013–2014	8021
2014–2015	1751
2015–2016	2137
2016–2017	2600

Tidal energy

Ocean energy can be explored and developed because 70% of the earth is ocean. Ocean energy can come from tidal waves, temperature gradients, and waves. Tidal energy comes from the tides' rising and falling. Since India has 7,500 km of coastline and over 336 islands in the Arabian Sea and Bay of Bengal, its tidal power can power turbines. Preliminary estimations suggest 40,000 MW of wave energy potential. Wave energy is estimated at 5–15 MW per shoreline length, depending on height. Given the average length of the Indian coastline, 6,000 km, the power potential is over 60000 MW. This quantity has power potential, but only 10% is used. (Hairat MK 2014)

Coal and fly ash speciation

According to studies from Indian coalfields and thermal power plants, the following table describes the speciation of Indian coal and fly ash found in thermal power plants, focussing on major oxides, trace elements, and mineral forms:

Table 3 Indian Coal and Fly Ash Specifications for Thermal Power Plants

Component	Indian Coal	Fly Ash (Post-Combustion)	Remarks / Source
Major Oxides	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , CaO, MgO, K ₂ O, Na ₂ O	SiO ₂ (35–60%), Al ₂ O ₃ (20–30%), Fe ₂ O ₃ (5–10%), CaO, MgO	Fly ash enriched in aluminosilicates and oxides (Vassilev et al., 2010)
Mineralogical Forms	Quartz, kaolinite, illite, pyrite, calcite, dolomite	Mullite, quartz, amorphous aluminosilicate glass, hematite	Combustion alters minerals; glassy phase dominates fly ash (Matjie et al., 2005)
Carbon Content	High (volatile matter 20–35%)	Low (typically <5% unburned carbon)	Dependent on combustion efficiency (Goodarzi, 2006)
Sulfur Forms	Pyritic S (major), organic S, sulfate S	Mostly as SO ₂ gas; some retained as CaSO ₄ in ash	Sulfur converted and partially trapped with Ca additives (Anthony & Granatstein, 2001)
Heavy Metals (Trace)	As, Pb, Hg, Cd, Cr, Ni, Zn, Cu, Se	Concentrated in fly ash: As, Hg, Pb, Cr, Cd (often enriched)	Toxic elements volatilize and condense on ash (Finkelman, 1994; Zhang et al., 2008)
Radioactive Elements	U, Th (naturally occurring in trace amounts)	Slight enrichment in fly ash due to concentration in residue	Radioactivity slightly higher in fly ash (Pandit et al., 2001)
REEs (Rare Earths)	Present in mineral matter (ppm level)	Slightly enriched in ash; Ce, La, Nd, Y, Sc	Potential recovery interest (Mayfield & Lewis, 2013)

Operating Temperature of Indian Coal and Fly Ash in Thermal Power Plants

The operational temperature during coal combustion in Indian thermal power plants usually surpasses 800°C, especially in Pulverised Coal Combustion (PCC) systems, which are extensively utilised for power generation. According to Vassilev et al. (2010), the furnace temperatures in PCC boilers range from 1,200 to 1,500°C, which is much higher than 800°C. Minerals are melted and consolidated at high temperatures, enabling efficient combustion and the generation of fly ash. Speight (2013) backs up the allegation, stating that coal-fired facilities must maintain combustion temperatures over 1,000°C to accomplish complete oxidation of carbon and volatile compounds. FBC systems attempt to reduce NO_x emissions and enhance the combustion efficiency of low-grade Indian coals by maintaining a working temperature between 800°C and 900°C (Anthony and Granatstein, 2001). Furthermore, Indian coals' high ash content makes them suitable for fluidized bed systems, which operate at temperatures lower than the melting point (about 850°C) to minimize slagging (Bhattarya and Chattopadhyay, 2002). As a result, the bulk of India's power is generated by PCC-based thermal plants, and while 800°C may be used in select FBC-based systems, it is usually lower than necessary. Several studies have indicated that thermal power plants in India, particularly those that burn bituminous and sub-bituminous coal, have combustion temperatures much beyond 800°C. For example, Gupta and Paul (2005) report that furnace temperatures in Indian pulverized coal boilers can exceed 1,200°C. This permits the ash to fuse well and aids total combustion, resulting in glassy fly ash with less crystalline phases. Similarly, Sinha and Banerjee (1997) report that conventional boilers may operate at temperatures ranging from 1,100°C to 1,500°C, with the precise range controlled by coal quality and boiler design. In addition to affecting combustion efficiency, these temperatures influence the shape and mineral makeup of the produced fly ash. Circulating fluidized bed combustion (CFBC) systems are often used in India to burn lignite and low-grade coal. These systems maintain a low combustion temperature, typically about 850°C, to reduce slag and NO_x emissions (Rao and Bhandari, 2003). Because of chemical speciation, lower-temperature fly ash has less glass and more unburned carbon than higher-temperature ash. Chakraborty et al. (2007) investigate how temperature differences in different boiler zones influence the physicochemical properties of ash particles. Zones above 1,300°C are recognized by full melting and the development of amorphous glass, whereas zones below 800°C create heterogeneous fly ash particles predominantly by partial melting of mineral elements. Heat is the most efficient temperature for volatilizing and redistributing hazardous trace metal compounds in fly ash, such as arsenic, selenium, and mercury (Das and Nandi, 2010).

Health Risk Problems Associated With Increasing Fly Ash and coal combustion

One of the many pollutants that influence land use, human health, and air, soil, and water quality worldwide is coal-fired thermal power plant pollution. Due to direct water contact, fly ash water impacts scale structure. Indian coal-fired thermal power stations release 105 MT of CCRs, damaging the environment. Electrostatic precipitators capture dry fly ash and semi-wet pond ash from thermal power station ash ponds. Most Indian thermal power facilities lack autonomous dry ash collection. Fly and bottom ash slurry typically ends up in an ash pond or lagoon. This impacts social, economic, and environmental factors.

Coal has radioactive elements. The composition and history of a geological formation determine its radioactive content. Flue gases from combustion emit volatile radionuclides like Pb210 and Po210. The lowest ash slag retains a lot of radioactivity. Some fly ash from coal-fired power stations enters the atmosphere, but most of the coal's radioactivity stays. Air pollution from coal-fired thermal power plants harms soil, water, plants, the ecosystem, and humans. Radon, a radioactive substance released into the atmosphere, endangers individuals who work in uranium mines, live in ordinary homes, and work in coal mining, cement manufacture, thermal power plants, etc. Fly ash from coal combustion may be a radioactive air contaminant.

CFA's physical characteristics and biological toxicity

Surface area, particle size, shape, stiffness, and intricate inner architecture affect how coal fly ash (CFA) enters and interacts with organisms. CFA particles in water or air create differing-sized clusters when joined. Sneezing can cause bigger airborne particles ($>10\text{ }\mu\text{m}$) to stick to the nasal mucosa or nasopharynx and be ejected. Particles can pass these barriers and cling to the lower airways. These particles travel with mucous when coughed. Particles under $5\text{ }\mu\text{m}$ can be easily passed via the airways and into the lungs. According to J.W. Finger They can harm alveoli and mucosal membranes, causing lung tissue fibrosis. Some of these small particles reach the lymphatic system via the alveolar gap and settle on the pulmonary hilum, a vital circulation site. Particles can enter the circulation by inhalation, oral intake, and skin penetration. Foroozandeh, P. (2016) found that workers exposed to high CFA concentrations at work are more likely to be exposed to it daily. Due to its smaller diameter ($200\text{ }\mu\text{m}$) than human pores, little CFA are likely to circulate through the skin, like most nanoscale particles. Any skin injuries or wounds can worsen this. Before reaching the intestinal mucosa, oral CFA particles pass via the oesophagus and stomach. These particles may enter intestinal epithelial cells. Enterocytes release vesicles to expel them. HJ Feuerborn (2017)

Many organ cells absorb blood-circulating CFA microparticles. Most CFA microparticles are spherical, however oval and irregular shapes alter cellular absorption. The study found that cells phagocytise spherical particles better than others. For instance, macrophages prefer spherical particles over lengthy ones. Hela cells phagocytose round particles more than rod-shaped ones. RAW264.7 macrophages prefer CdTe quantum dot-cystine microspheres to rectangular disc microparticles. Spherical forms are more likely to touch cell membranes, increasing the possibility of receptor engagement and transport into cells via receptor-dependent or receptor-independent mechanisms. P. Foroozandeh. Cancer cells are stiffer than normal cells, therefore the immune system is more sensitive to phagocytosing them. The energy barrier rises and more receptors are needed to absorb soft particles because they deform when they touch the cell membrane. CFA particles' chemical and physical qualities determine how, how much, and how they enter mammals, contributing to their biological toxicity.

CFA's chemical characteristics and biological toxicity

Coal combustion process details determine coal fly ash (CFA) chemical makeup. CFA consists mostly of scaffolds and attachments. Silicon, aluminium, iron, oxygen, and calcium make up most of CFA's solid core scaffolds. Attachments are non-covalently attached organic and inorganic compounds to the scaffold matrix's pores and crevices. These attachments can leak in some circumstances. Some inorganic materials are radioactive, heavy metals like cadmium, chromium, and lead, and non-metals like arsenic, selenium, and boron (Bednar et al., 2013; Baranov, 2020). Polychlorinated biphenyls and polycyclic aromatic hydrocarbons are among several environmental pollutants. Understanding the leaching behaviour of CFA's chemical components helps choose the best coal for electric power plants, optimise coal burning, and determine how much CFA pollutes the environment. Predicting CFA's health and ecological risks requires knowing its toxic components' biological tolerance and half-life. (Goodarzi, F.,2017)

Table 4. CFA's and its leachates' possible effects on human systems.

Toxic components from CFA	Systems	Target Organ	Adverse effects	Refer
Mercury (Hg)	Nervous system	Eyes, Brain	Hg reduces brain calcium-ATPase function, increases lipid peroxidation, and impairs vision.	(Schutter, M.E., Fuhrmann, J.J., 2001)
Polychlorinated biphenyls (PCBs)	Nervous system digestive system	Liver, brain	PCBs can cause oxidative stress and neurobehavioral issues in newborns..	(Bednar et al., 2013; Baranov et al., 2020).
Micron-sized particles	Respiratory system	Respiratory tract	Children with CFA were more likely to develop asthma.	(Sears, L., et al., 2020.)
Chromium (Cr)	Respiratory system,	Lung, nasal, lymphocytes	Genotoxicity and lung and nasal cancer are caused by Cr (VI).	(Satarug, S.,2018)
Lead (Pb)	Nervous system, circulatory system	Vessel, ears, brain	Pb can cause learning problems, sluggish development, low IQ, hearing loss, high blood pressure, and other health issues..	(Goodarzi, F.,2017)
Cadmium (Cd)	Circulatory system	Vascular, Myocardium	Cd may induce atherosclerosis and cardiac muscle cell metabolism issues.	(Schilling, C.J.,2016)
Polycyclic aromatic hydrocarbons (PAHs)	locomotor system	Muscle	PAHs-induced oxidative stress causes muscular atrophy and locomotor dysfunction.	(Sears, C.G.,2017)
Boron (B)	Nervous system circulatory system	Eyes, intestine immune organs, cardiovascular	B may increase perinatal mortality, neurological and cardiovascular disorders, ocular irritation, intestinal cell apoptosis, and hyp immunity..	(Santos-Sacramento, L, 2019)
Arsenic (As)	Digestive system urinary system reproductive system	Intestinal tract kidney liver	Can induce Type 2 diabetes, obesity, newborn illnesses, etc..	(Sambandam, B.,2016)

Health Impacts

Reddy and Yellapu (2017) state that fine particulate matter (PM_{2.5}) from fly ash emissions causes bronchitis, asthma, and cardiovascular stress, which are conditions related to the respiratory system and the heart. The buildup of arsenic, lead, mercury, and cadmium in human tissues has been linked to neurological impairment, developmental delays, and renal failure (Finkelman, 1994; Zhang et al., 2008). The presence of silica-rich ash dust, which can cause silicosis, increases the risk of lung cancer among plant staff and nearby populations.

(Bhattacharya et al., 2006). According to Maiti et al. (2005), metals from ash ponds at Singrauli and Korba power stations seep into groundwater, posing a threat to drinking water.

Environmental Impacts

Adriano et al. (1980) discovered that fly ash deposit alters soil pH, reduces microbiological activity, and lowers fertility. The presence of hazardous metals such as Cr, As, and Se in leachates discharged from unlined ash disposal sites has polluted surface and groundwater sources. Fly ash impairs air quality by increasing particle concentrations, which contributes to air pollution and climate change. Soil contaminated with fly ash is a source of heavy metals that plants absorb. These metals accumulate in plants and animals, affecting ecosystems (Sinha and Banerjee, 1997).

CONCLUSION

Indian thermal power stations use coal to generate electricity. However, the readily accessible coal has low calorific value and high ash content. Managing fly ash and climate change are only two of the several environmental repercussions of thermal power plants' significant reliance on coal. This section digs deeper into the investigation of CFA, a dangerous pollutant found in industrial waste. Among the numerous topics discussed are CFA's physical and chemical characteristics, its detrimental affects on living organisms, measures for preventing dangerous chemical leaks, human health epidemiology, and cell entry paths. Despite extensive investigation, considerable gaps remain. These include CFA measurement in diverse species, human exposure routes, CFA distribution and absorption throughout the body, and CFA health effects. Air, soil, and water pollution, land usage, and health concerns are caused by globally spread coal-fired thermal power stations. Fly ash from thermal power stations must be properly disposed of for environmental protection. Researching all fly ash uses is advised. Fly ash bricks, cement, pottery, roads, and other construction materials are strong, inexpensive, and ecologically benign. To determine real exposure levels, future research should create a geographical database of coal and ash chemistry across several thermal power plants in India, incorporating environmental and human biomonitoring investigations. To understand element behaviour and speciation, sequential extraction, X-ray absorption spectroscopy, and nanoparticle characterisation are needed. Longitudinal health studies in affected populations and life cycle assessments (LCA) that account for India's climate and groundwater are essential. Fly ash and REE recovery safety research can boost economic and environmental sustainability. These suggestions will support evidence-based fly ash management practices to protect public health.

REFERENCES

- [1] Ahmaruzzaman, M. A review on the utilization of fly ash. *Prog. Energy Combust. Sci.* **2010**, 36, 327–363.
- [2] Bhatt, A.; Priyadarshini, S.; Mohanakrishnan, A.A.; Abri, A.; Sattler, M.; Techapaphawit, S. Physical, chemical, and geotechnical properties of coal fly ash: A global review. *Case Stud. Constr. Mater.* **2019**, 11, e00263.
- [3] Vassilev, S.V.; Vassileva, C.G. A new approach for the classification of coal fly ashes based on their origin, composition, properties, and behaviour. *Fuel* **2007**, 86, 1490–1512.
- [4] Wang, M.; Chen, D.; Wang, H.; Gao, W. A review on fly ash high-value synthesis utilization and its prospect. *Green Energy Resour.* **2024**, 2, 100062.
- [5] Wirth, X.; Glatstein, D.A.; Burns, S.E. Mineral phases and carbon content in weathered fly ashes. *Fuel* **2019**, 236, 1567–1576.
- [6] Alterary, S.S.; Marei, N.H. Fly ash properties, characterization, and applications: A review. *J. King Saud Univ. Sci.* **2021**, 33, 101536.
- [7] Yao, Z.T.; Ji, X.S.; Sarker, P.K.; Tang, J.H.; Ge, L.Q.; Xia, M.S.; Xi, Y.Q. A comprehensive review on the applications of coal fly ash. *Earth-Sci. Rev.* **2015**, 141, 105–121.
- [8] F. Xi, S.J. Davis, P. Ciais, D. Crawford-brown, D. Guan, C. Pade, T. Shi, M. Syddall, J. Lv, L. Ji, L. Bing, J. Wang, W. Wei, Substantial global carbon uptake by cement carbonation, 1 (2016). <https://doi.org/10.1038/NGEO2840>
- [9] P.J.M. Monteiro, S.A. Miller, A. Horvath, Towards sustainable concrete. *Nat. Publ. Gr.* 16, 698–699 (2017). <https://doi.org/10.1038/nmat4930>
- [10] S.A. Miller, F.C. Moore, Climate and health damages from global concrete production. *Nat. Clim. Change* (2020). <https://doi.org/10.1038/s41558-020-0733-0>
- [11] Chindaprasirt A. Horvath, P.J.M. Monteiro, Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%. *Environ. Res. Lett.* 11, 074029 (2016)
- [12] T. Hemalatha, A. Ramaswamy, A review on fly ash characteristics—towards promoting high volume utilization in developing sustainable concrete. *J. Clean. Prod.* 147, 546–559 (2017). <https://doi.org/10.1016/j.jclepro.2017.01.114>

- [13] R. Siddique, Utilization of silica fume in concrete: review of hardened properties. *Resour. Conserv. Recycl.* 55, 923–932 (2011). <https://doi.org/10.1016/j.resconrec.2011.06.012>
- [14] H. Zhao, W. Sun, X. Wu, B. Gao, The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures. *J. Clean. Prod.* 95, 66–74 (2015). <https://doi.org/10.1016/j.jclepro.2015.02.050>
- [15] Y.H.M. Amran, R. Alyousef, H. Alabduljabbar, M. El-Zeadani, Clean production and properties of geopolymer concrete; a review. *J. Clean. Prod.* (2020). <https://doi.org/10.1016/j.jclepro.2019.119679>
- [16] A.R.K. Gollakota, V. Volli, C.M. Shu, Progressive utilisation prospects of coal fly ash: a review. *Sci. Total Environ.* (2019). <https://doi.org/10.1016/j.scitotenv.2019.03.337>
- [17] J.L. Provis, Cement and concrete research alkali-activated materials. *Cem. Concr. Res.* 114, 40–48 (2018). <https://doi.org/10.1016/j.cemconres.2017.02.009>
- [18] L.N. Assi, K. Carter, E. Deaver, P. Ziehl, Review of availability of source materials for geopolymer/sustainable concrete. *J. Clean. Prod.*, 121477 (2020). <https://doi.org/10.1016/j.jclepro.2020.121477>
- [19] Blissett, R. S., & Rowson, N. A. (2012). A review of the multi-component utilisation of coal fly ash. *Fuel*, 97, 1–23. <https://doi.org/10.1016/j.fuel.2012.03.024>
- [20] Izquierdo, M., & Querol, X. (2012). Leaching behaviour of elements from coal combustion fly ash: An overview. *International Journal of Coal Geology*, 94, 54–66. <https://doi.org/10.1016/j.coal.2011.10.006>
- [21] Querol, X., Alastuey, A., López-Soler, A., Plana, F., & Andres, J. M. (2001). Physico-chemical characteristics and leaching behavior of fly ashes from Spanish coal-fired power stations. *Fuel*, 80(13), 1659–1671. [https://doi.org/10.1016/S0016-2361\(01\)00050-6](https://doi.org/10.1016/S0016-2361(01)00050-6)
- [22] Spears, D. A. (2012). The use of coal ash in geological and environmental studies. *International Journal of Coal Geology*, 94, 69–72. <https://doi.org/10.1016/j.coal.2012.02.003>
- [23] Vassilev, S. V., & Vassileva, C. G. (2007). A new approach for the classification of coal fly ashes based on their origin, composition, properties, and behavior. *Fuel*, 86(10–11), 1490–1512. <https://doi.org/10.1016/j.fuel.2006.11.030>
- [24] Ward, C. R. (2002). Analysis and significance of mineral matter in coal seams. *International Journal of Coal Geology*, 50(1–4), 135–168. [https://doi.org/10.1016/S0166-5162\(02\)00117-6](https://doi.org/10.1016/S0166-5162(02)00117-6)
- [25] Adriano, D. C., Page, A. L., Elseewi, A. A., Chang, A. C., & Straughan, I. R. (1980). Utilization and disposal of fly ash and other coal residues in terrestrial ecosystems: A review. *Journal of Environmental Quality*, 9(3), 333–344. <https://doi.org/10.2134/jeq1980.00472425000900030001>
- [26] Finkelman, R. B. (1994). Trace elements in coal: Environmental and health significance. *Biological Trace Element Research*, 47(1–3), 203–208. <https://doi.org/10.1007/BF02790154>
- [27] Goodarzi, F. (2006). Characteristics and composition of fly ash from Canadian coal-fired power plants. *Fuel*, 85(10–11), 1418–1427. <https://doi.org/10.1016/j.fuel.2005.11.030>
- [28] Matjie, R. H., Bunt, J. R., & Schobert, H. H. (2005). Mineral matter transformation during Sasol-Lurgi gasification: A XRD and SEM/EDS study. *Fuel*, 84(7–8), 823–830. <https://doi.org/10.1016/j.fuel.2004.11.004>
- [29] Vassilev, S. V., Menendez, R., Alvarez, D., & Diaz-Somoano, M. (2010). Phase-mineral and chemical composition of coal fly ashes as a basis for their multicomponent utilization. *Fuel*, 89(2), 384–401. <https://doi.org/10.1016/j.fuel.2009.07.022>
- [30] Zhang, L., Liu, Y., Zeng, L., Gao, J., & Liu, J. (2008). Environmental characterization of leachates from coal fly ash. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 30(14–15), 1326–1333. <https://doi.org/10.1080/15567030601113472>
- [31] Singh, D.; Yadav, V.K.; Ali, D.; Soni, S.; Kumar, G.; Dawane, V.; Chaurasia, T.P. Isolation and Characterization of Siderophores Producing Chemolithotrophic Bacteria from the Coal Samples of the Aluminum Industry. *Geomicrobiol. J.* **2022**, 1–7.
- [32] Xiahou, Q.; Springer, C.H.; Mendelsohn, R. The effect of foreign investment on Asian coal power plants. *Energy Econ.* **2022**, 105, 105752.
- [33] Nazar, R.; Srinivasan, S.L.; Kanudia, A.; Asundi, J. Implication of emission regulation on cost and tariffs of coal-based power plants in India: A system modelling approach. *Energy Policy* **2021**, 148, 111924.
- [34] Edianto, A.; Trencher, G.; Matsubae, K. Why do some countries receive more international financing for coal-fired power plants than renewables? Influencing factors in 23 countries. *Energy Sustain. Dev.* **2022**, 66, 177–188.

- [35] Marinina, O.; Nevskaya, M.; Jonek-Kowalska, I.; Wolniak, R.; Marinin, M. Recycling of coal fly ash as an example of an efficient circular economy: A stakeholder approach. *Energies* **2021**, *14*, 3597.
- [36] Adeleye, B.N.; Osabohien, R.; Lawal, A.I.; de Alwis, T. Energy use and the role of per capita income on carbon emissions in African countries. *PLoS ONE* **2021**, *16*, e259488.
- [37] Chateau, B.; Lapillonner, B. Energy Demand in the Transport Sector. In *Energy Demand: Facts and Trends: A Comparative Analysis of Industrialized Countries*; Chateau, B., Lapillonner, B., Eds.; Springer: Vienna, Austria, 1982; pp. 73–134.
- [38] Singh, D; Li, S.; Zhao, Y.; Yao, Q. Mechanism on the contribution of coal/char fragmentation to fly ash formation during pulverized coal combustion. *Proc. Combust. Inst.* **2019**, *37*, 2831–2839.
- [39] Kotelnikova, A.; Rogova, O.; Karpukhina, E.; Solopov, A.; Levin, I.; Levkina, V.; Proskurnin, M.; Volkov, D. Assessment of the structure, composition, and agrochemical properties of fly ash and ash-and-slug waste from coal-fired power plants for their possible use as soil ameliorants. *J. Clean. Prod.* **2022**, *333*, 130088.
- [40] Nandi, M.; Vyas, N.; Vij, R.K.; Gupta, P. A review on natural gas ecosystem in India: Energy scenario, market, pricing assessment with the developed part of world and way forward. *J. Nat. Gas Sci. Eng.* **2022**, *99*, 104459.
- [41] Hasse, C.; Debiagi, P.; Wen, X.; Hildebrandt, K.; Vascellari, M.; Faravelli, T. Advanced modeling approaches for CFD simulations of coal combustion and gasification. *Prog. Energy Combust. Sci.* **2021**, *86*, 100938.
- [42] Wei, Z.; Baiquan, L.; Tong, L. Construction of Pingdingshan coal molecular model based on FT-IR and ¹³C-NMR. *J. Mol. Struct.* **2022**, *1262*, 132992.
- [43] Yuan, Q.; Zhang, Y.; Wang, T.; Wang, J.; Romero, C.E. Mechanochemical stabilization of heavy metals in fly ash from coal-fired power plants via dry milling and wet milling. *Waste Manag.* **2021**, *135*, 428–436.
- [44] Park, H.; Wang, L.; Yun, J.-H. Coal beneficiation technology to reduce hazardous heavy metals in fly ash. *J. Hazard. Mater.* **2021**, *416*, 125853.
- [45] Chen, Y.; Chen, F.; Zhou, F.; Lu, M.; Hou, H.; Li, J.; Liu, D.; Wang, T. Early solidification/stabilization mechanism of heavy metals (Pb, Cr and Zn) in Shell coal gasification fly ash based geopolymer. *Sci. Total Environ.* **2022**, *802*, 149905.
- [46] Anthony, E. J., & Granatstein, D. L. (2001). Sulfation phenomena in fluidized bed combustion systems. *Progress in Energy and Combustion Science*, *27*(2), 215–236. [https://doi.org/10.1016/S0360-1285\(00\)00021-0](https://doi.org/10.1016/S0360-1285(00)00021-0)
- [47] Baxter, L. (2005). Biomass-coal co-combustion: Opportunity for affordable renewable energy. *Fuel*, *84*(10), 1295–1302. <https://doi.org/10.1016/j.fuel.2004.09.023>
- [48] Demirbaş, A. (2005). Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Progress in Energy and Combustion Science*, *31*(2), 171–192. <https://doi.org/10.1016/j.pecs.2005.02.002>
- [49] Goodarzi, F. (2006). Characteristics and composition of fly ash from Canadian coal-fired power plants. *Fuel*, *85*(10–11), 1418–1427. <https://doi.org/10.1016/j.fuel.2005.11.030>
- [50] International Energy Agency (IEA). (2022). *World Energy Outlook 2022*. <https://www.iea.org/reports/world-energy-outlook-2022>
- [51] Senior, C. L., Johnson, S. A., & Sarofim, A. F. (2000). Behavior of mercury in coal combustion systems. *Fuel Processing Technology*, *63*(2), 197–213. [https://doi.org/10.1016/S0378-3820\(99\)00081-0](https://doi.org/10.1016/S0378-3820(99)00081-0)
- [52] Speight, J. G. (2013). *The Chemistry and Technology of Coal* (3rd ed.). CRC Press.
- [53] Tillman, D. A. (2000). Biomass cofiring: The technology, the experience, the combustion consequences. *Biomass and Bioenergy*, *19*(6), 365–384. [https://doi.org/10.1016/S0961-9534\(00\)00049-0](https://doi.org/10.1016/S0961-9534(00)00049-0)
- [54] Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. *Nature* 2012;488:294–303. doi: 10.1038/nature11475.
- [55] Singh R. Energy sufficiency aspirations of India and the role of renewable resources: Scenarios for future. *Renew Sustain Energy Rev* 2017;81:2783–95. doi: 10.1016/j.rser.2017.06.083.
- [56] Srinivasan S, Kholod N, Chaturvedi V et al. Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. *Appl Energy* 2017;210:673–84. doi: 10.1016/j.apenergy. 2017.04.079.
- [57] Singh AK, Parida SK. National electricity planner and use of distributed energy sources in India. *Sustain Energy Technol Assessments* 2013;2:42–54. doi: 10.1016/j.seta.2013.03.001.
- [58] Palit D, Bandyopadhyay KR. Rural electricity access in India in retrospect: A critical rumination. *Energy Policy* 2017;109:109–20. doi: 10.1016/j.enpol.2017.06.025.

- [59] Chattopadhyay D. Modelling renewable energy impact on the electricity market in India. *Renew Sustain Energy Rev* 2014;31:9–22. doi: 10.1016/j.rser.2013.11.035.
- [60] Qin Y, Zhang M, Hiller JE. Theoretical and experimental studies on the daily accumulative heat gain from cool roofs. *Energy* 2017;129:138–47. doi: 10.1016/J.ENERGY.2017.04.077.
- [61] Qin Y, He H. A new simplified method for measuring the albedo of limited extent targets. *Sol Energy* 2017;157:1047–55. doi: 10.1016/J. SOLENER.2017.09.027.
- [62] Dehghani Madvar M, Alhuvi Nazari M, Tabe Arjmand J et al. Analysis of stakeholder roles and the challenges of solar energy utilization in Iran. *Int J Low-Carbon Technol* 2018;13:438–51. doi: 10.1093/ijlct/cty044.
- [63] Govindaraju VGRC, Foon C. The dynamic links between CO 2 emissions, economic growth and coal consumption in China and India. *Appl Energy* 2013;104:310–8. doi: 10.1016/j.apenergy.2012.10.042.
- [64] Hairat MK, Ghosh S. 100 GW solar power in India by 2022 – A critical review. *Renew Sustain Energy Rev* 2017;73:1041–50. doi: 10.1016/j. rser.2017.02.012.
- [65] Bhide A, Monroy CR. Energy poverty: A special focus on energy poverty in India and renewable energy technologies. *Renew Sustain Energy Rev* 2011;15:1057–66. doi: 10.1016/j.rser.2010.11.044.
- [66] Vassilev, S. V., et al. (2010). *Fuel*, 89(2), 384–401.
- [67] Matjie, R. H., et al. (2005). *Fuel*, 84(7–8), 823–830.
- [68] Goodarzi, F. (2006). *Fuel*, 85(10–11), 1418–1427.
- [69] Anthony, E. J., & Granatstein, D. L. (2001). *Progress in Energy and Combustion Science*, 27(2), 215–236.
- [70] Finkelman, R. B. (1994). *Biological Trace Element Research*, 47, 203–208.
- [71] Zhang, L., et al. (2008). *Energy Sources, Part A*, 30(14–15), 1326–1333.
- [72] Pandit, G. G., et al. (2001). *Radiation Protection Dosimetry*, 93(4), 291–295.
- [73] Mayfield, D. B., & Lewis, A. S. (2013). *Environmental Science & Technology*, 47(16), 9567–9576.
- [74] Adriano, D. C., et al. (1980). *Journal of Environmental Quality*, 9(3), 333–344.
- [75] Bhattacharya, S., et al. (2006). *Science of the Total Environment*, 370(1), 133–138.
- [76] Finkelman, R. B. (1994). *Biological Trace Element Research*, 47, 203–208.
- [77] Goodarzi, F. (2006). *Fuel*, 85(10–11), 1418–1427.
- [78] Maiti, S. K., et al. (2005). *Environmental Monitoring and Assessment*, 102(1), 263–276.
- [79] Pandit, G. G., et al. (2001). *Radiation Protection Dosimetry*, 93(4), 291–295.
- [80] Reddy, K. S., & Yellapu, N. (2017). *Environmental Science and Pollution Research*, 24(7), 6535–6543.
- [81] Vassilev, S. V., et al. (2010). *Fuel*, 89(2), 384–401.
- [82] Zhang, L., et al. (2008). *Energy Sources Part A*, 30(14–15), 1326–1333.
- [83] Feuerborn, H.J., et al., Global aspects on coal combustion products., *Proc. Eurocoalash Conf. Univ. DundeeScotl. Great Br*, Vol. 26, 2019, pp. 1–17.
- [84] Finger, J.W., et al., 2016. Chronic ingestion of coal fly-ash contaminated prey and its effects on health and immune parameters in juvenile American alligators (*Alligator mississippiensis*). *Arch. Environ. Contam. Toxicol.* 71, 347–358.
- [85] Foroozandeh, P., Aziz, A.A., 2018a. Insight into cellular uptake and intracellular trafficking of nanoparticles. *Nanoscale Res. Lett.* 13, 1–12.
- [86] Foroozandeh, P., Aziz, A.A., 2018b. Insight into cellular uptake and intracellular trafficking of nanoparticles. *Nanoscale Res. Lett.* 13, 1–12.
- [87] Goodarzi, F., et al., 2008. Assessment of elements, speciation of As, Cr, Ni and emitted Hg for a Canadian power plant burning bituminous coal. *Int. J. Coal Geol.* 74, 1–12.
- [88] Sambandam, B., et al., 2015. Characterization of coal fly ash nanoparticles and their induced in vitro cellular toxicity and oxidative DNA damage in different cell lines.
- [89] Santos-Sacramento, L., et al., 2021. Human neurotoxicity of mercury in the Amazon: a scoping review with insights and critical considerations. *Ecotoxicol. Environ. Saf.* 208, 111686.
- [90] Satarug, S., et al., 2010. Cadmium, environmental exposure, and health outcomes. *Environ. Health Perspect.* 118, 182–190.
- [91] Schilling, C.J., et al., 1988. A survey into the respiratory effects of prolonged exposure to pulverised fuel ash. *Br. J. Ind. Med* 45, 810–817.

- [92] Schutter, M.E., Fuhrmann, J.J., 2001. Soil microbial community responses to fly ash amendment as revealed by analyses of whole soils and bacterial isolates. *Soil Biol. Biochem.* 33, 1947–1958.
- [93] Sears, C.G., Zierold, K.M., 2017. Health of children living near coal ash. *Glob. Pedia Health* 4, 2333794×17720330.
- [94] Sears, L., et al., 2020. Associations of the behavioral assessment and research system (BARS) neurobehavioral outcomes with attention problems in children living near coal ash storage sites. *Neurotoxicology* 81, 11–17.
- [95] Shen, Z., et al., 2018. Membrane wrapping efficiency of elastic nanoparticles during endocytosis: Size and shape matter. *ACS Nano* 13, 215–228.
- [96] Shim, I., et al., 2012. Subacute inhalation toxicity assessment of fly ash from industrial waste incinerators. *Inhal. Toxicol.* 24, 741–750.
- [97] Bhattacharya, C., & Chattopadhyay, H. (2002). Combustion characteristics of high ash Indian coal. *Fuel*, 81(4), 495–500.
- [98] Speight, J. G. (2013). *The Chemistry and Technology of Coal* (3rd ed.). CRC Press.
- [99] Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010). An overview of the chemical composition of biomass. *Fuel*, 89(5), 913–933.
- [100] Gupta, R., & Paul, B. (2005). Mineralogical and morphological characteristics of fly ash from Indian thermal power plants. *Fuel*, 84(11), 1417–1424.
- [101] Sinha, R. K., & Banerjee, S. (1997). Characteristics and utilization of fly ash from thermal power plants in India. *Journal of Environmental Science & Engineering*, 39(4), 225–231.
- [102] Rao, A. K., & Bhandari, R. K. (2003). Fluidized bed combustion of low-grade Indian coal. *Energy Conversion and Management*, 44(18), 2763–2773.
- [103] Chakraborty, A., et al. (2007). Influence of combustion temperature on fly ash characteristics. *International Journal of Coal Geology*, 71(3), 240–252.
- [104] Das, S. K., & Nandi, B. K. (2010). Leaching behavior of trace elements from fly ash. *Journal of Hazardous Materials*, 177(1–3), 226–231.
- [105] Jaworek, A.; Sobczyk, A.T.; Czech, T.; Marchewicz, A.; Krupa, A. Recovery of cenospheres from solid waste produced by coal-fired power plants. *Clean. Waste Syst.* **2023**, 6, 100109.
- [106] Meena, R.; Hashmi, A.W.; Ahmad, S.; Iqbal, F.; Soni, H.; Meena, A.; Al-Kahtani, A.A.; Pandit, B.; Kamyab, H.; Payal, H.; et al. Influence of fly ash on thermo-mechanical and mechanical behavior of injection molded polypropylene matrix composites. *Chemosphere* **2023**, 343, 140225.
- [107] Wang, G.; Li, Z.; Yan, J.; Qian, Y.; Wei, Y.; Li, D.; Guo, S. Value-added utilization of coal fly ash in polymeric composite decking boards. *J. Mater. Res. Technol.* **2023**, 23, 4199–4210.
- [108] Basu, M.; Pande, M.; Bhadoria, P.; Mahapatra, S. Potential fly-ash utilization in agriculture: A global review. *Prog. Nat. Sci.* **2009**, 19, 1173–1186.