OPEN ACCESS

Volume: 4

Issue: 2

Month: May

Year: 2025

ISSN: 2583-7117

Published: 10.04.2025

Citation:

Vijay Kumar Meshram, Rajesh Kumar Misra, Prabhat Kumar Tiwari "A Review on Physicochemical Characteristics of Coal Ash and Soil" International Journal of Innovations in Science Engineering and Management, vol. 4, no. 2, 2025, pp. 155–160.

DOI:

10.69968/ijisem.2025v4i2155-160

A Review on Physicochemical Characteristics of Coal Ash and Soil

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Abstract

The yearly output of coal fly ash, which supports industrial production and economic growth, amounts to tens of millions of tonnes. With millions of "coal combustion residue (CCR)", burning coal has been one of the most common energy sources over the last 200 years. The permanent chemical and physical modification of soils to improve their physical characteristics is known as soil stabilisation. Portland cement, fly ash, and lime are just a few of the chemical additions that may be used to stabilise. This article reviews the many studies on the composition and physicochemical properties of soil and coal ash. It concluded that coal ash amendment increases soil nutrient content—particularly sodium, calcium, magnesium, sulphur, potassium, and phosphorus—most prominently in the humus horizon. While biomass showed modest gains, coal ash's low organic matter and slow nutrient release limited significant improvements in crop growth. Moreover, excessive or repeated application, especially of unmodified coal ash, poses serious environmental concerns by elevating heavy metal levels (Pb, Cr, Cu) in soil and crops like pakchoi, thereby increasing pollution risks over time. Therefore, careful management and possible pre-treatment of coal ash are crucial for safe agricultural use.

Keywords; Coal ash, Fly ash (FA), Coal combustion residue (CCR), Soil stabilization, Crop growth, Heavy metal, etc.

INTRODUCTION

The annual production of hundreds of millions of tonnes of coal fly ash (CFA) worldwide is a direct consequence of the rapid increase in coal consumption, which has been driven by economic and industrial development. Burning coal results in the production of solid and gaseous contaminants, mostly ash and slag. When coal is burned in thermal power plants, dust removers gather fine coal fly ash, a generally solid by product [1]. The efficiency and complexity of storing coal fly ash are also significantly increased by continuous mining, which is another significant source of micro coal fly ash. Coal fly ash is used nowadays for a number of purposes, including backfilling mining subsidence, supplying raw materials for the manufacture of cement, and treating wastewater by acting as an absorbent. Dependent upon the content and composition of the ash, the specific application is determined. These reuse methods have the potential to mitigate the environmental hazards associated with the accumulation of coal fly ash [2]. Utilising coal fly ash as a basic material for subsequent use is feasible from the circular economy perspective. The exploitation of coal fly ash has been observed, resulting in multiple environmental damages, despite the fact that it has the potential to enhance soil structure and boost soil organic matter. For example, it has been shown that too much coal fly ash reduces the soil's ability to retain water and store nutrients [3]. Furthermore, the inclusion of coal fly ash to the mixture can result in the pollution of ground water and sediment due to its elevated levels of heavy metals. A substantial reduction in "soil bulk density and macroaggregates" is frequently observed as a result of the incorporation of coal fly ash. However, poor commercial crop yields and significant soil nutrient loss have previously been experienced by the regional coal fly ash soil. In order to increase agricultural production in coal fly ash soil, it is important to investigate methods [4], [5].

Coal combustion residuals (CCR) are byproducts of burning coal and include fluidised bed combustion ash, fly ash, bottom ash, boiler slag and flue gas desulfurization residues. More than 70% of waste coal ash is classified as fly ash (FA), which are small particles with sizes ranging from 0.5 mm to 300 mm that are caught by particulate control equipment. In 2015, the United States used 53% fly ash, India 43%, and China 70%. There is a great deal of room for expanded use [6]. Fly ash reuse may substitute costly or non-renewable materials and reduce disposal volumes and expenses. Portland cement concrete is made using fly ash as a supplemental cementitious material (SCM). The characteristics of hardened concrete are enhanced by fly ash when employed in SCM due to its pozzolanic as well as hydraulic activity. "Fly ash" has been applied to concrete in amounts ranging from 15% to 25% by mass, and structural applications may benefit from high dosages of 40% to 60%. The longevity of hardened concrete and the qualities of new concrete may both be significantly impacted by the addition of fly ash. Concrete size and type, exposure circumstances before and after installation, building methods, and the amount and makeup of other materials in the mixture all influence how much fly ash changes the characteristics of concrete [7]. The appropriate replacement level for every application is thus not a single one. Fly ashes' potential for reuse is influenced by their physical and chemical characteristics. Fly ash has a variety of potential re-use options, including geotechnical applications such as soil stabilisation for "roadways, backfill for excavations, mine fill, trenches, and retaining walls, landfill liners or coverings", and as a geopolymer material [8]. Value-added components, including "magnetites, aluminosilicates, unburned carbon, and cenospheres", have been segregated through the development of numerous separation techniques to enhance the re-use of fly ash. Among fly ash's most useful components are cenospheres. Numerous applications may benefit from these qualities, which include high compressive strength, minimal water absorption, light weight, chemical inertness, and superior heat resistance. Cenospheres have a variety of applications, including heat exchangers, mullite-coated diesel engine parts, and aluminium reclamation. In the building sector, they may be added to cement to generate lightweight workable materials [9].

Coal ash

Burning coal in coal-fired power stations is the main source of coal ash, also known as "coal combustion residuals or CCRs" [10]. Among the several byproducts of burning coal are coal ash, which includes:

Fly ash: an extremely fine, powdery substance that is mostly silica and is produced in a boiler by burning finely powdered coal.

Bottom ash: The coal furnace's bottom is where a coarse, angular ash particle develops because it is too big to be taken up into the smokestacks.

Boiler slag: "Molten bottom ash" from cyclone and slag tap furnaces is transformed into smooth, glassy pellets when cooled with water.

Flue gas desulfurization material: It may be a dry powdery combination of sulfites and sulphates or a wet sludge made of calcium sulfite or calcium sulphate, which is a byproduct of lowering "sulphur dioxide emissions from a coal-fired boiler".

Effect of Coal ash

As well as "aluminium, antimony, barium, beryllium, boron, chlorine, cobalt, manganese, molybdenum, nickel, thallium, vanadium, and zinc, coal ash" typically contains heavy metals such as arsenic, lead, mercury, cadmium, chromium, and selenium, depending on the location of the coal's mining. Cancer and effects on the neurological system, including retardation in development, behavioural issues, and cognitive impairments, may result from ingesting, drinking, or inhaling these toxicants [11]. In addition, they may result in birth abnormalities, gastrointestinal disorders, renal disease, respiratory distress, lung disease, heart damage, reproductive issues, and stunted bone development in youngsters. Living near a coal ash disposal site has been linked to an increased risk of cancer and other illnesses, according to research by "the Environmental Protection Agency (EPA)". For individuals who reside in close proximity to an unlined damp "ash pond (surface impoundment)" and obtain their potable water from a well, the likelihood of contracting cancer from arsenic-contaminated water may be as high as 1 in 50. One of coal ash's most prevalent and hazardous contaminants is arsenic. Additionally, the Environmental Protection Agency discovered that the likelihood of "cadmium, lead, and other hazardous metals" causing harm is elevated in residences near ash basins [12].

Disposal and Recycling

Since coal ash has a substantial environmental impact, there is disagreement regarding the most effective approach to managing the refuse. Some power stations dump coal ash into a river, while others dispose of it in landfills or surface impoundments. The abandoned mine is sometimes refilled with a little quantity of dry coal ash. Additionally, it may be recycled into a variety of products. For a long time, fly ash has been added to concrete, grout, and cement. As a fill material, it is also used to stabilise road beds. Similarly, bottom ash is employed to stabilise roads by filling them with snow or regulating their snow accumulation [13]. By reducing the amount of space that coal ash would otherwise occupy in landfills, its reuse lowers greenhouse gas emissions. Because the production of concrete and bricks contributes significantly to "greenhouse gas emissions", utilising fly ash to decrease the quantity of brick or concrete created helps to lower greenhouse gas emissions. The repurposing of coal ash has economic advantages as well. This includes savings from employing coal ash rather of alternative more expensive resources, lower disposal expenses, and higher sales income from new coal ash products. Reusing fly ash lessens its negative impact on the environment, but others argue that using it to ma ke building materials is risky because seeping chemicals might contaminate the air [14].

Soil stabilization

To improve the physical properties of soils, soil stabilisation involves the persistent modification of their physical and chemical properties. In order to improve a sub-grade's ability to sustain pavements and foundations, stabilisation may either raise the soil's shear strength or regulate its shrink-swell characteristics. From granular materials to expansive clays, stabilisation may be utilised to treat a variety of sub-grade materials. Portland cement, fly ash, and lime are just a few of the chemical additions that may be used to stabilise. An essential part of any stabilisation project is proper design and testing [15]. This makes it possible to develop design requirements and figure out the right rate of chemical addition and mixing to obtain the required technical qualities. Benefits of the stabilisation process may include: increased resistance (R) values; decreased plasticity and permeability; decreased pavement thickness; removal of excavation, material handling, and base imports; assistance with compaction; allows access to project areas in all weather conditions. Soil modification, which can be referred to as either "mud drying or soil conditioning", is another form of soil treatment that is closely associated with soil stabilisation [16]. The difference is that, while some stabilisation is inherent in soil modification, stabilisation can significantly increase a material's shear strength so that it can be included in the project's structural design, while soil modification is only a way to lower a soil's moisture content to speed up construction. The final application of the soil structure, the current moisture content, and, finally, the financial advantage offered may be the deciding factors in soil alteration vs. soil stabilisation. Spreaders for chemical additives, "soil mixers (reclaimers), water trucks, deep lift compactors, motor graders, and portable pneumatic storage containers" are some of the tools used in the stabilisation and modification procedures [17].

LITERATURE REVIEW

(Li et al., 2024) [4] In this research, a field experiment was carried out in China's Hebei province to examine the impacts of "coal fly ash as a soil amendment". The aim of this research is to examine how the activities of the soil microbial community and the physicochemical characteristics of the soil react to "soil amendments and carrier soil in coal fly ash soil". Overall, our findings show that by enhancing soil microbial activities, using "coal fly ash soil" as an amendment may improve soil sustainability. These results serve as a guide for the creation and use of soil amendments made from coal fly ash.

(Johnson Jeyaraj & Sankararajan, 2024) [18] According to the combined characteristics of soils and water, appropriate fly ash (FA) was chosen for agricultural use in this research. According to a research using "energy dispersive X-ray spectroscopy (EDX)", FAs include important macro and micronutrients that assist reduce soil nutrient levels and increase plant yield. Because both FAs are alkaline in nature, it is advised to utilise them at sites 1 and 2, which have acidic soil conditions. Because of its fineness content, FA may increase the sandy loam soils' ability to retain water at sites 2, 3, and 4. With high iron FA-STPS, Site 1's iron shortage may be corrected. To increase agricultural efficiency, it is advised to apply the best FA depending on soil and water conditions.

(Akimbekov et al., 2023) [19] With the promise of long-term productivity and environmental protection, fly ash (FA) soil additives made from coal production wastes have gained popularity in agriculture in many nations around the globe in recent years. FA was modified in this work using low-rank coal-derived HA, and the adsorption/desorption characteristics were assessed for several pH values and incubation durations. After 60 days of treatment, the physicochemical and biological properties of the soil were enhanced when the resulting HA-FA composite was applied to "test soil in controlled pot tests". Moreover, the activity of polyphenol oxidase and dehydrogenase and "the physiological diversity of the soil microbial community" were positively correlated with HA-FA amendment. According to the findings, the HA-FA composite generally improves soil quality and might help support sustainable soil management techniques both now and in the future.

(Petrović et al., 2023) [20] Using a variety of criteria, such as "pH, total nitrogen and organic carbon content", main oxides (Al2O3, CaO, and SiO2), macronutrients (Ca, K, Mg, P, and S), textural information, and mineralogical data, this research characterised two CCR landfills of comparable age (about 50 years). Its comprehensive strategy sought to characterise the landfills' ability to hold water, nutrients, and toxins as well as identify markers of soil formation. The pH drop, secondary mineral formation "(e.g., ettringite, hydrotalcite, gypsum, and calcite), and C: N ratio" variations in both landfills were indicative of pedogenesis. Montmorillonite may be one of the primary elements speeding up pedogenesis in Plaški. Unburned coal particles are the primary source of organic matter, according to 13C NMR spectra, whereas 29Si NMR spectra revealed that bare ash samples had a greater depolymerisation of a non-crystalline portion than vegetated ash samples.

(Sun et al., 2021) [21] For four seasons in a row, pakchoi were grown in pots with brown soil supplemented with "fly ash or bottom ash" for this investigation. Pb, Cr, and Zn dispersed in acetic acid concentrations rose with repeated plantings, while the overall amounts in the four Pb, Cr, and Cu fractions dropped. The application of 15% fly ash resulted in the least fresh weight of pakchoi. The danger of heavy metals in soils altered with coal ash was negligible, according to the Nemerow Pollution Index (NPI) calculated using the Environmental Protection Standards. "Pb, Cr, and Zn's Risk Assessment Code (RAC)" progressively increased with subsequent plantings, and Zn ultimately attained a medium level. Coal ash application posed a risk of soil pollution, and the study confirmed that it had "phytotoxic effects" on pakchoi.

(Lungu et al., 2019) [22] A by-product of burning coal with high heat, coal ash (CA) is regarded as a complicated solid waste worldwide, and there is increasing concern about how to properly dispose of it. A few studies suggest that coal ash could be utilised as a soil additive in order to reduce the obstacles associated with its disposal. "Nodulation and pod formation" were shown to be unaffected by the coal ash amendment, however plant height was found to be severely impacted ($p<0.05$). The addition of coal ash considerably decreased the retention of soil moisture at both higher (pF 4.6) and lower (saturation) suctions. Coal ash's moderate moisture retention capacity and ability to promote nodulation—a crucial component of nitrogen fixation—prove its enormous potential for application as an agricultural amendment, particularly in the often underutilised Vertisols.

(Howladar & Islam, 2016) [23] Consequently, the primary focus of this investigation is the evaluation of the various properties and applications of coal ash in order to ensure the safety of the environment in the vicinity of the facility. Therefore, evaluating coal ash's physical, chemical, and engineering characteristics for categorisation, appropriate uses, and secure surroundings under direct field inquiry and laboratory analysis are the main goals of this study. Good quality ash is indicated by the main and minor chemical features of coal ash that have been analysed. The results replicate the effect of the addition of coal ash with sand and cement to enhance the quality of mixtures, specifically by boosting the consistency, compressive strength, tensile strength, and bearing capacity. Conversely, the hydraulic conductive ability of concrete or soil is reduced.

(Wyszkowski et al., 2014) [24] With the application of various organic materials, such as manure, straw, and bark, the research sought to ascertain the long-term impact of meliorating dosages of hard coal ash on the level of certain elements in soil. The surface stratum of soil experienced a particularly significant increase in sodium, followed by calcium, magnesium, sulphur, potassium, and phosphorus, in which the values decreased. Only magnesium and sulphur showed a progressive decrease in concentration along with an increase in depth. The 51-75 cm stratum had the lowest concentrations of calcium and phosphorus, while the 26-50 cm zone had the lowest concentrations of potassium. Nineteen years after their application, the materials added to the soil to lessen the impact of ash produced by burning hard coal had no discernible effect on the elements' composition.

CONCLUSION

The review highlights the multifaceted impact of coal ash amendment on soil physicochemical characteristics and plant growth. Coal ash application led to a noticeable increase in soil nutrients—most prominently sodium, followed by calcium, magnesium, sulphur, potassium, and phosphorus—particularly in the humus horizon. The extent of nutrient enrichment was generally dose-dependent. Although coal ash improved biomass production in some cases, such as in finger millet, its low organic matter content limited significant enhancement of dry matter yield and nodulation. Additionally, soil structure played a role in nutrient circulation, with well-aggregated soils showing better support for plant growth. However, adverse effects were observed in pakchoi, particularly at higher application rates (15%), with reductions in growth and biomass yield. Furthermore, repeated use of coal ash resulted in increased bioavailability and accumulation of heavy metals like Pb, Cr, and Cu in the soil and plants, raising concerns about environmental and health risks. The unmodified use of both bottom and fly ash poses pollution hazards due to heavy metal mobility. Overall, while coal ash offers potential benefits as a soil amendment, its application must be carefully managed to mitigate long-term contamination risks.

REFERENCES

[1] J. Kalembkiewicz, D. Galas, and E. Sitarz-Palczak, "The physicochemical properties and composition of biomass ash and evaluating directions of its applications," Polish J. Environ. Stud., vol. 27, no. 6, pp. 2593–2604, 2018, doi: 10.15244/pjoes/80870.

[2] Z. Jin, J. Huang, J. C. Hower, and H. Hsu-Kim, "Predictive Assessment of the Chemical Composition of Coal Ash in Reserve at U.S. Disposal Sites," Environ. Sci. Technol., 2025, doi: 10.1021/acs.est.4c12705.

[3] D. M. Tripathi, D. Singh, and S. Tripathi, "Influence of Coal Fly-Ash on Soil Properties and Productivity of Chickpea Crop in Semi-Arid Region of Bundelkhand," Curr. World Environ, vol. 15, no. 1, pp. 127–136, 2020, doi: 10.12944/cwe.15.1.16.

[4] F. Li et al., "Responses of soil microbial community activities and soil physicochemical properties to coal fly ash soil amendment," Ann. Microbiol., vol. 74, no. 1, 2024, doi: 10.1186/s13213-024-01758-7.

[5] A. Yadav, Pooja, Anjali, and Mahesh, "E-Waste Management in India: Challenges and Roadmap for Sustainable Future," Int. J. Innov. Sci. Eng. Manag., vol. 4, no. 1, pp. 56–63, 2025, doi: 10.69968/ijisem.2025v4i156-63.

[6] A. Bhatt, S. Priyadarshini, A. Acharath Mohanakrishnan, A. Abri, M. Sattler, and S. Techapaphawit, "Physical, chemical, and geotechnical properties of coal fly ash: A global review," Case Stud. Constr. Mater., vol. 11, p. e00263, 2019, doi: 10.1016/j.cscm.2019.e00263.

[7] S. Beddu et al., "Sustainable Energy Recovery From the Malaysian Coal Bottom Ash and the Effects of Fineness in Improving Concrete Properties," Front. Energy Res., vol. 10, no. October, pp. 1–19, 2022, doi: 10.3389/fenrg.2022.940883.

[8] B. Muratov et al., "Physico-Chemical Study of the Possibility of Utilization of Coal Ash by Processing as Secondary Raw Materials to Obtain a Composite Cement Clinker," J. Compos. Sci., vol. 7, no. 6, pp. 1–15, 2023, doi: 10.3390/jcs7060234.

[9] P. Liu, L. Bai, and Y. Wen, "Experimental Study on Coal Ash to Improve Southern Paddy Field," J. Phys. Conf. Ser., vol. 2941, no. 1, 2025, doi: 10.1088/1742-6596/2941/1/012068.

[10] D. Valeev and A. Kondratiev, "Current State of Coal Fly Ash Utilization: Characterization and Application," Materials (Basel)., vol. 16, no. 1, pp. 1–6, 2023, doi: 10.3390/ma16010027.

[11] R. Šulc, M. Šídlová, P. Formáček, R. Snop, F. Škvára, and A. Polonská, "A Study of Physicochemical Properties of Stockpile and Ponded Coal Ash," Materials (Basel)., vol. 15, no. 10, 2022, doi: 10.3390/ma15103653.

[12] M. Gilewska, K. Otremba, and M. Kozłowski, "Physical and chemical properties of ash from thermal power station combusting lignite. A case study from central Poland," J. Elem., vol. 25, no. 1, pp. 279–295, 2020, doi: 10.5601/jelem.2019.24.4.1886.

[13] A. Tomczyk, Z. Sokołowska, and P. Boguta, "Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects," Rev. Environ. Sci. Biotechnol., vol. 19, no. 1, pp. 191–215, 2020, doi: 10.1007/s11157-020-09523-3.

[14] A. Oarga-Mulec, S. Skok, T. Simčič, and J. Mulec, "Characteristics and impact of aged coal ash with slag emplaced in a karst cave: the case of Divaška jama, Slovenia," Sci. Rep., vol. 11, no. 1, pp. 1–10, 2021, doi: 10.1038/s41598-021-02842-7.

[15] S. Xu, Y. Zhang, J. Guo, A. Wu, X. Xiang, and H. Sun, "Experimental and modeled analysis of contaminant mobility in coal fly ash landfills under continuous rainfall regimes," Sci. Rep., vol. 15, no. 1, p. 2758, 2025, doi: 10.1038/s41598-025-86591-x.

[16] N. Guo, L. Bai, Y. Yang, and F. Wang, "Feasibility study on coal based solid waste as a soil additive," Sci. Rep., vol. 15, no. 1, pp. 1–14, 2025, doi: 10.1038/s41598-025-88227-6.

[17] P. Nanda and S. Nanda, "Geotechnical Characterization of Indian Coal Ash: A Review," no. December, pp. 63–76, 2022, doi: 10.1007/978-981-97-2704-9_7.

[18] N. Johnson Jeyaraj and V. Sankararajan, "Study on the characterization of fly ash and physicochemical properties of soil, water for the potential sustainable agriculture use - A farmer's perspectives," Int. Rev. Appl. Sci. Eng., vol. 15, no. 1, pp. 95–106, 2024, doi: 10.1556/1848.2023.00661.

[19] N. S. Akimbekov, I. Digel, K. T. Tastambek, K. Tagayev, S. O. Bastaubayeva, and A. K. Marat, "Utilization of Humic-Loaded Fly Ash as a Slow-Release Amendment for Soil Quality Improvement," ES Mater. Manuf., vol. 22, pp. 1–16, 2023, doi: 10.30919/esmm967.

[20] M. Petrović et al., "Physicochemical and mineral characteristics of soil materials developed naturally on two ∼ 50 years old coal combustion residue disposal sites in Croatia," Catena, vol. 231, no. October, 2023, doi: 10.1016/j.catena.2023.107338.

[21] W. Sun et al., "Environmental risk assessment of coal-ash-amended soil based on continuous planting of pakchoi," Am. J. Biochem. Biotechnol., vol. 17, no. 2, pp. 192–204, 2021, doi: 10.3844/ajbbsp.2021.192.204.

[22] O. N. Lungu, M. Hamakona, and E. Phiri, "EFFECT OF COAL ASH ON SOIL WATER RETENTION, AND SOYBEAN (Glycine Max) GROWTH," Int. J. Agric. Environ. Bioresearch, vol. 4, no. 02, pp. 15–23, 2019.

[23] M. F. Howladar and M. R. Islam, "A study on physico-chemical properties and uses of coal ash of Barapukuria Coal Fired Thermal Power Plant, Dinajpur, for environmental sustainability," Energy, Ecol. Environ., vol. 1, no. 4, pp. 233–247, 2016, doi: 10.1007/s40974-016-0022-y.

[24] M. Wyszkowski, A. Chełstowski, Z. Ciećko, and R. Szostek, "Long-time effect of hard coal ash on the content of some elements in soil," J. Ecol. Eng., vol. 15, no. 1, pp. 55–60, 2014, doi: 10.12911/22998993.1084203.