Environmental impact of fly ash contaminated soil of the surrounding area of Kolaghat thermal power station in West Bengal, India

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Abstract
Fly ash is a byproduct of coal combustion in thermal power plants posing significant environmental concerns owing to its possible to pollute soil, air, and water. The second largest coal-based thermal power station in West Bengal (India) is Kolaghat Thermal Power Station (KTPS) which generates large quantities of fly ash, often deposited in the surrounding environment over a long period. This study investigates the physicochemical and microbial properties of soils contaminated by fly ash of KTPS near the power station to assess its impact on soil quality and agricultural sustainability.

The current study indicated that the levels of heavy metals (HMs) like Pb, Cr, As, and Fe in fly ash-contaminated soils (FCS) were notably greater than those in the control soil. Physiochemical characteristics like pH, bulk density (BD), electrical conductivity (EC), total organic matter (TOM), water holding capacity (WHC), and NPK content differed concerning control soil affecting the nearby agricultural land. Colony-forming units were used as a common indicator of microbial biomass. Microbial activity was changed with the alteration of different physicochemical properties of the soil. It was found that bacterial activity was higher in all of the collected FCS samples. So, the findings provide valuable insights into the long-term consequences of fly ash deposition and suggest strategies to mitigate environmental damage and to promote sustainable agricultural practices.

Keywords: Fly ash, soil pollution, heavy metals, physicochemical parameters, microbiota.

Introduction

Coal-based thermal power stations are among the leading sources of electricity generation worldwide. Therefore, coal serves as the primary fuel for energy production[18]. However, coal combustion results in the generation of substantial quantities of fly ash, a fine particulate residue that poses significant environmental challenges[6,39]. Fly ash primarily comprises of inorganic minerals, trace elements, and unburned carbon, which can adversely affect the surrounding environment when released into the atmosphere or deposited onto nearby soil. The improper handling and disposal of fly ash have raised concerns regarding soil contamination, environmental degradation, and potential risks to human and ecological health[36].

The coal-based Kolaghat Thermal Power Station (KTPS) is located on the west bank of the Rupnarayana River and is close to Macheda station in the Purba Medinipur district of West Bengal, India. It is the second-largest thermal power plant in West Bengal as well as one of the popular leading thermal power stations in India. Although it has been providing a significant contribution to the State's power sector, environmental concerns such as heavy metals contamination of agricultural land have emerged a long time ago[29]. A large amount of ash from the KTPS is dumped into the nearby land and water bodies, leading to pollution of water, air, and soil, including the Rupnarayana river[24]. Only 325 acres of land are now owned by the factory, and there are five ash ponds in operation. However, 1250 acres of land are needed by the KTPP to dispose of the fly ash produced during its whole lifespan from 1984[5].

Human health and agricultural productivity both are hampered due to the overflow of the pollutant up to 5 to 6-kilometer areas of KTPS. The majority of heavy metals including lead (Pb), arsenic (As), mercury (Hg), chromium (Cr), nickel (Ni), cadmium (Cd), silver (Ag), uranium (U), and others, have little physiological and biochemical effects in plants and animals. They are regarded as non-essential metals that cause tissue and cellular damage which can result in several illnesses and negative consequences[2]. Metal ions interact with DNA to cause DNA damage, which can then result in cell cycle modulation, cancer, and other conformational alterations of various metabolic pathways[22]. The physicochemical characteristics of soil such as its pH, electrical conductivity, organic carbon content, and nutrient availability, can all be altered by fly ash contamination. Additionally, the heavy metal contents in fly ash such as arsenic, lead, chromium etc. can disrupt soil microbial activity, thereby affecting soil fertility and crop productivity[16,31]. Understanding the physicochemical and microbial properties of fly ash-contaminated soil is critical for assessing its impact on agricultural practices and local ecosystems.

The objective of the current study is to assess the current state of the agricultural land surrounding the Kolaghat

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Thermal Power Station (KTPS) in Purba Medinipur, West Bengal, India (22°24′56″N, 87°52′12″E) following the release of coal combustion byproducts into the local environment (Figure 1). The toxic contribution of the KTPS in the adjacent soil was assessed in terms of physico-chemical properties and microbial load in the surrounding soil. We examined the physico-chemical properties of the fly ash-contaminated soil from six locations in the surrounding areas of KTPS to understand the soil conditions for plant growth. We also quantified metal content (Pb, As, Cr, and Fe) in all the samples of the study areas to know the risk of heavy metal contamination in the soil. Besides, we studied the colony-forming unit (CFU) of bacteria and fungi in all the samples to analyze the toxic contribution of KTPS.

Material and Methods

Collection of fly ash and fly ash fly-contaminated soil: Fly ash-contaminated soil (FCS) from the six locations of the study area (viz. Katchora Kharisha, Mandar Gachha, Baragechhe, Amalhanda, and Denachara) was collected (Figure 1). The soil of the sampling stations was abbreviated as FCS1 to FCS6 respectively. From each location, five soil samples were taken randomly from 0 - 30 cm below the soil surface in a sterilized large plastic bag with proper labeling. All five samples of the same weight at each location were mixed thoroughly. Control soil sample was collected from Jiakhali (a location, not contaminated by Fly ash) of Purba Medinipur district, West Bengal, about 25 km away from KTPS following the above process.

The composite sample was treated as a representative one for the specific location. Fly ash samples of the same weight were collected from different ash ponds which were mixed thoroughly to prepare a composite sample. Following 10 days of air drying, each sample was sieved using a standard 2-2.37 mm and finally stored at room temperature (28±2°C) for further study.

Soil testing: To determine the level of physico-chemical properties including pH, EC, particle density total organic matter, total organic carbon, water holding capacity, bulk density, NPK content, and heavy metals (Pb, As, Cr, and Fe) concentration in the polluted soil, samples were tested following the relevant standard method with some modifications. The pH was tested in a suspension of soil and distilled water (1:2.5) using a pH meter following the test method of IS-2720-26[12]. Electrical conductivity was determined using an electrical conductivity meter in soil and distilled water suspension (1:2), following the test method of IS-14767[13]. Bulk density and particle density were measured by using a metal cylinder (Pycnometer that is a specific gravity bottle) and weight machine following a previous method[3].

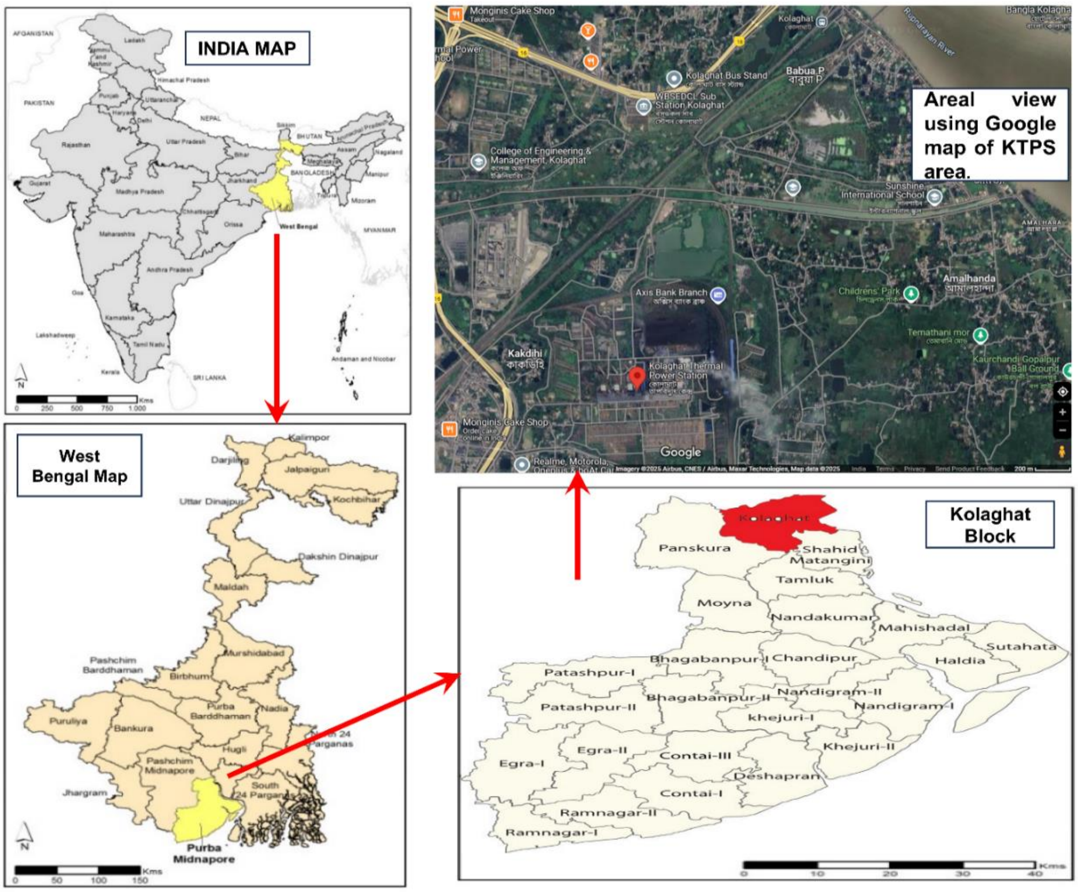

Figure 1: Study area of the fly ash contaminated soil of the surrounding area of KTPS in West Bengal, India (This figure was modified and adopted from Gayen et al[9]).

Soil nitrogen was tested by the acid-based titration method[17]. Total organic carbon (TOC) was tested using a modified standard method[37]. Total organic matter (TOM) was measured by using a Muffle furnace, sieve, and oven following the described method by Schulte and Hopkins[32] applying the formula:

Total Organic Matter (%) = [(WS1-WS2) / WS1] ×100

where WS1 = Weight of Soil at the temperature of 105 ^{0}C and WS2 = Weight of Soil at the temperature of 400 ^{0}C.

All the heavy metals contents (Pb, As, Cr, and Fe) including phosphorus (P) and potassium (K) were measured using Energy Dispersive X-ray Fluorescence (EDXRF) instrument (Model- NEX CG; Serial- CG1542; Rigaku technologies).

Estimation of colony forming unit in the soil samples: The colony forming unit (CFU) of soil microorganisms was determined by following steps:

Preparation of soil sample solution and serial dilution: One test tube was taken with 10 ml of sterilized distilled water, and 1 gm of the sample was added in the test tube. It is treated as the original solution, and other seven test tubes are filled with 9 ml of water (sterile distilled) each. Afterward, 1 ml of the suspension from the above original solution was taken and added to a test tube containing 9 ml of water (distilled) to prepare a 10^{-1} diluted solution. One ml of solution from the 10^{-1} dilution was taken to transferred into another test tube filled with 9 ml of water (distilled) to get a dilution of 10^{-2}. Thus, the process was followed serially to get 10^{-7} diluted solution[38]. Each time, the vortex was done.

Plate Preparation: For each sample, three plates were taken for fungal growth, and three plates were taken for bacterial growth. Relevant media were taken in the plates. Then 0.2 ml of 10^{-7} dilution was inoculated on culture media and spread properly. There were three replicates for both fungal growth and bacterial growth of each sample. Then, the bacterial plates and fungal plates were incubated for 48 h and 72 h respectively at 37 °C. Following incubation, the number of colonies was meticulously counted, and the mean value of three replicates for each sample was taken. The microbial colony was counted using the following equation:

CFU/ml = (No. of colony × Inverse of dilution taken) / volume of inoculum taken

As the original solution of 10 ml had a 1 gm sample, the formula is:

CFU/gm DW= CFU/ml × 10

Statistical analysis: All values are represented as the mean of three replicates ± Standard deviation (mean ± SD). The data were analyzed to test the statistical significance ($p < 0.05$) using One-way Analysis of Variance (ANOVA), and Duncan's multiple study was applied by the Statistical Package for Social Sciences (Version 16.0) software.

Results and Discussion

Physicochemical properties: The physico-chemical characteristics of soil have significance in monitoring environmental pollution. The results of the physicochemical properties of the collected fly ash-contaminated soil (FCS) samples of the studied stations are represented in figure 2.

pH and electrical conductivity: The pH of the collected fly ash contaminated soil (FCS) of the studied stations ranged from 6.15±0.11 (FCS4) to 6.89±0.03 (FCS1), and electrical conductivity (EC) from 480.46±11.05 (FCS5) to 810.76±7.95 (FCS4). The soil of all the stations was acidic, and the pH value was lower than 7.61±0.04 (NCS) due to fly ash (pH 6.16±0.04) contamination as one of several factors. All the fly ash polluted soils have higher EC than NCS (509.93±8.34 µs/cm) other than FCS5 (480.46±11.05 µs/cm). EC of the FA was higher (1332.43±25.45 µs/cm) than the control soil (509.93±8.34).

It has been noticed previously that the acidic property of the FA is due to the higher sulphur content of the used coal[21]. Therefore, it could be significantly indicated that the acidic nature of the FCS samples of the studied area was due to fly ash contamination over a long period. Soil pH may alter the solubility of the salt. The soluble salts that are present in the soil are referred to as soil salinity. Increasing acidity of the soil with a low pH value causes dissociation of the electrolytes. This results in high soluble salt content in the soil. So, Soil pH was an important factor other than depth, temperature, water holding capacity etc. which affected the EC also[23].

This study also revealed that soil electrical conductivity was higher with increasing acidity, supporting the previous studies[1,11].

Bulk density and particle density: BD of the collected fly ash contaminated soil (FCS) of the studied stations ranged from 1.12±0.07 gm/cm^3 (FCS6) to 1.31±0.05 gm/cm^3 (FCS4) whereas the PD ranged from 1.64±0.03 gm/cm^3 (FCS6) to 1.78±0.04 gm/cm^3 (FCS4 and FCS5). The value of the BD for FCS - samples was observed to be lower than the control soil (1.43 gm/cm^3). The bulk density and particle density of FA were 1.04±0.05 gm/cm^3 and 1.84 ±0.05 gm/cm^3 respectively. The same mode of the result was also noticed in some previous studies which also depicted that bulk density had decreased with increasing aeration in the soil due to contamination of fly ash[8,15,26].

Total organic matter and organic carbon: Total organic matter and organic carbon in the FCS samples were decreased from the control. The decreasing order of organic matter of the collected FCS samples was NCS (5.02%) > FCS5 (4.87%) > FCS4 (4.84%) > FCS1 (4.42%) > FCS6 (4.05%) > FCS3 (3.65%) > FCS2 (2.68%) whereas the decreasing order of organic carbon was - NCS (2.94%) > FCS5 (2.87%) > FCS4 (2.83%) > FCS1 (2.55%) > FCS6 (2.34%) > FCS3 (2.12%) > FCS2 (1.56%).

Total organic matter and organic carbon in the FA sample were 2.87±0.02% and 1.47±0.04% respectively. Quite a low amount of organic Carbon in the coal fly ash has been reported in this investigation. A recent study has described that fly ash cannot enhance the carbon content[30]. Therefore, such mode of result regarding TOM and TOC in the present study was mostly due to fly ash contamination as it contained low levels of organic matter and organic carbon.

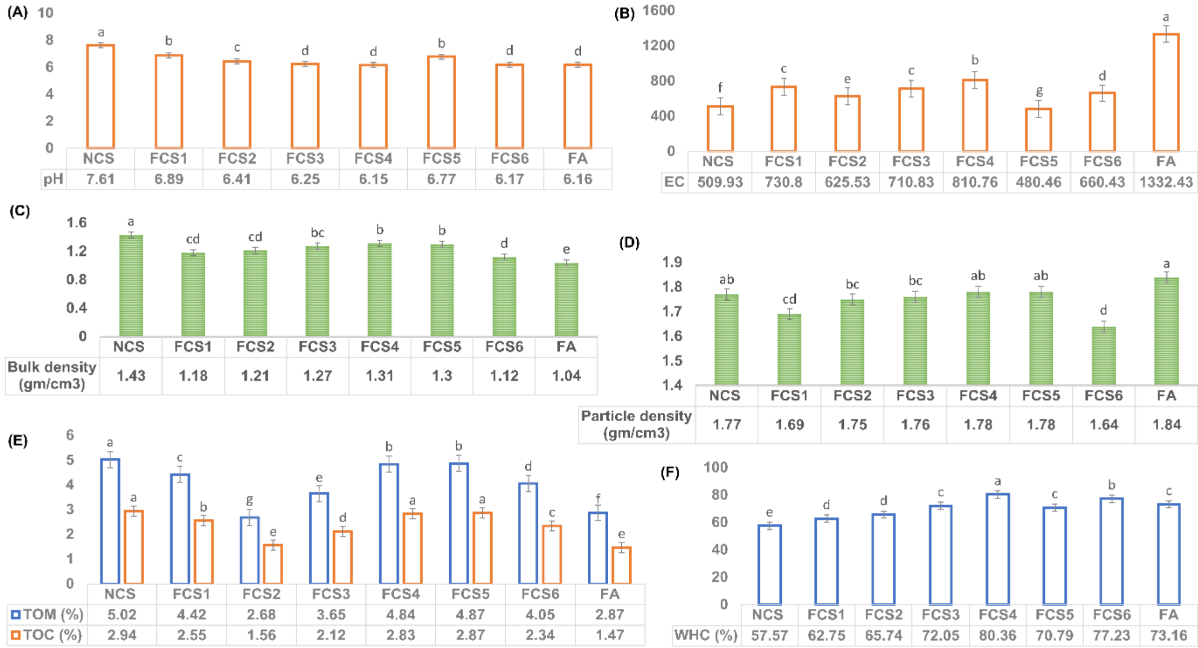

Figure 2: Column graph showing A) pH, B) electrical conductivity, C) bulk density, D) particle density, E) total organic matter (TOM), total organic carbon (TOC), and F) water holding capacity (WHC) of the collected control soil sample (NCS) and fly ash contaminated soil (FCS) samples of KTPS surrounding stations and fly ash (FA). Different letters indicate statistically significant variations ($p < 0.05$) based on Duncan's multiple comparison test and bars represent the standard error (± SE).

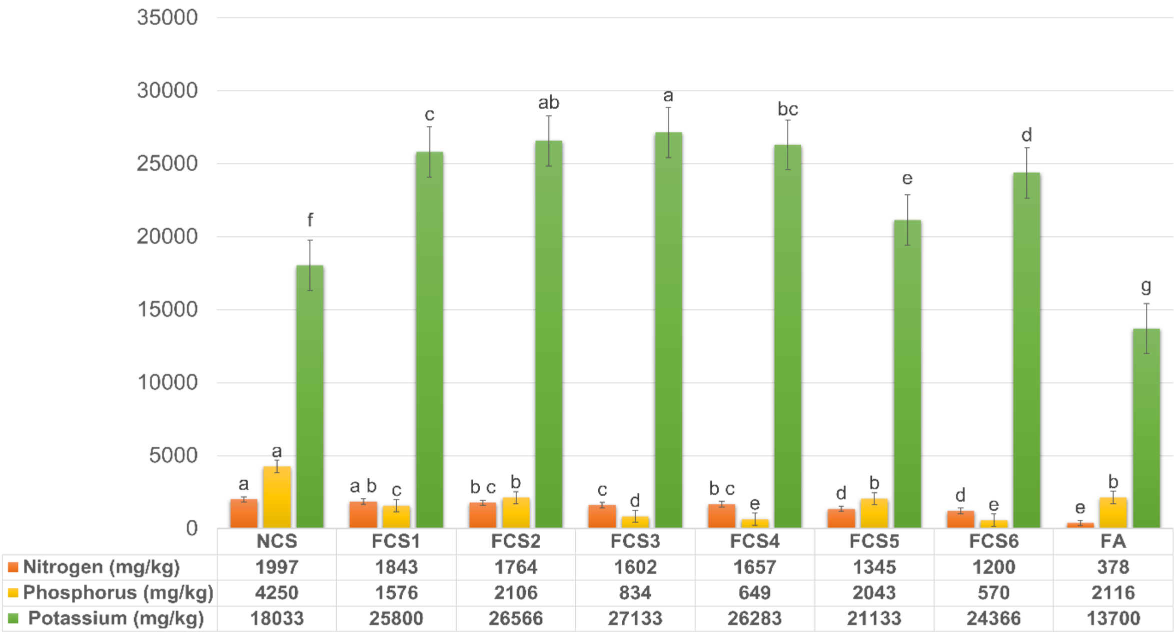

Figure 3: Column graph showing NPK values comparatively of the collected control soil sample (NCS) and fly ash contaminated soil (FCS) samples of KTPS surrounding areas and fly ash (FA). Different letters indicate statistically significant variations ($p < 0.05$) based on Duncan's multiple comparison test and bars represent the standard error (± SE).

Water holding capacity: The water holding capacity (WHC) of the FCS samples was higher than the NCS (Control). The increasing order was NCS (57.57%) < FCS1 (62.75%) < FCS2 (65.74%) < FCS5 (70.79%) < FCS3 (72.05%) <FCS6 (77.23%) <FCS4 (80.63%). In the case of FCS4 and FCS6, the water holding capacity was higher than FA (73.16 ±0.66%), and it could be due to higher organic matter including FA pollution in the soil of the studied stations. Fly ash contamination generally decreases the bulk density of the soil, which in turn helps to enhance water retention capability, including improvement of soil porosity[11]. So, the result regarding the WHO would advocate the scenario of FA contamination of the study area.

NPK status: Available nitrogen was recorded highest in control soil (1997.33±11.01 mg/kg) followed by decreasing concentration in all the FCS samples. Nitrogen content in fly ash was 378.6±27.12 mg/kg. Available phosphorus content in the soil samples of the studied area was found to be lower compared to the control soil (4250±122.88 mg/kg). The potassium concentration of the studied area was recorded highest in FCS3 (27133.33±152.75 mg/kg) and lowest in FCS6 (24366.66±493.28 mg/kg). The average values of nitrogen, phosphorus, and potassium of the six stations of the studied area were 1569.08±248.33 mg/kg, 1296.77±700.32 mg/kg, and 25213.88±372.86 mg/kg respectively. The average values showed that nitrogen and phosphorus content was lower than in the control soil whereas the potassium content was higher compared to the control (18033.33±152.75 mg/kg). The overall result is represented in figure 3.

In general, the use of coal FA on rice fields with low organic carbon did not enhance available phosphorus and nitrogen. The amount of organic carbon, nitrogen, and phosphorous in the coal fly ash employed in this investigation was quite low. Hence, the result in this study indicated that the NPK status of the area was variously affected due to different levels of fly ash accumulation in the cultivated land as well as due to the application of chemical fertilizers by the farmers[28].

Heavy metal concentration: In this study, the concentration of heavy metals like Pb, As, Cr, Mo, and Fe (mg/kg) in all the soil samples including fly ash were tested. The results for the FCS samples are presented in table 1. A guideline for permissible limits or maximum threshold concentration of the toxic metals in the soil prescribed by various agencies is presented in table 2.

Lead: Lead (Pb) is one of the moderately poisonous heavy metals, even in a small quantities[35]. The result revealed that the lead content (mg/kg) in the FCS samples of different stations of the KTPS surrounding area ranged from 30.66±0.73 mg/kg (FCS6) to 43.36±2.04 mg/kg (FCS1) with a mean value of 37±4.99 mg/kg (Table 1). The lead content of each station and also the average value of the studied area was higher than the control soil sample i.e. NCS (15.9±0.45 mg/kg). Lead content became higher due to the pollution of FA in which Pb concentration was highest (58.26±0.32 mg /kg).

Arsenic: Arsenic (As) is one of the extremely poisonous toxic heavy metals. The maximum arsenic (As) content was found in the FCS4 sample (14.26±0.38 mg/kg) whereas the minimum arsenic content was in the FCS6 sample (7.02±1.45 mg/kg). Both the values were higher than the control soil (2.47±0.16 mg/kg). Even in the case of FCS3 (13.2±0.63 mg/kg) and FCS4 (14.26±0.38 mg/kg), arsenic content was significantly higher than the FA (10.41±0.52 mg/kg). The mean value of arsenic in the soil of KTPS surrounding area based on six stations was 10.4±2.77 mg/kg (Table 1). Such results could be due to FA contamination as well as excessive use of groundwater, chemical fertilizers, pesticides, weedicides, and insecticides during cultivation[31].

Chromium: Chromium (Cr) is a moderately poisonous metal and its long-term consumption can cause serious health damages[35]. In the study, the control soil contained 74.73±6.42 mg/kg chromium whereas all the FCS samples of the KTPS surrounding area had higher concentrations of Cr than the control.

Table 1
Heavy metals content (mg/kg DW) in the control soil (NCS), collected fly ash contaminated soil (FCS) samples and fly ash (FA).

Soil Samples	Heavy Metals (mg/kg DW)			
	Lead (Pb)	Arsenic (As)	Chromium (Cr)	Ferrous (Fe)
NCS (Cont.)	15.9±0.45^{a}	2.47±0.16^{a}	74.73±6.42^{a}	32833.33±305.50^{b}
FCS1	43.36±2.04^{f}	8.55±0.94^{c}	139.00±1.00$^{d, e}$	36366.66±416.33^{d}
FCS2	37.26±0.75^{e}	9.75±0.27^{cd}	118.33±10.96^{c}	33866.66±503.32^{c}
FCS3	42.20±0.72^{f}	13.2±0.63^{e}	130.33±2.88^{d}	51566.66±51.66^{f}
FCS4	35.36±0.56^{d}	14.26±0.38^{e}	141.00±1.73^{e}	51733.33±602.77^{f}
FCS5	33.20±0.62^{c}	9.62±0.26$^{c, d}$	117.00±4.58^{c}	43233.33±351.18^{e}
FCS6	30.66±0.73^{b}	7.02±1.45^{b}	94.46±3.47^{b}	36266.66±208.16^{d}
FA	58.26±0.32^{g}	10.41±0.52^{d}	189.33±5.13^{f}	26166.66±115.47^{a}

[Values represent the mean of three replicates ± SD. Values are statistically significant with respect to control at $p < 0.05$; a–f: the same letters indicate no significant difference between treatment groups at $p < 0.05$]

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The amount of chromium varied from 94.46±3.47 mg/kg (FCS6) to 141 ±1.73 mg/kg (FCS4) with a mean value of 123.35 ±17.35 mg/kg (Table 1). Hence the mode of higher concentration of Cr in the investigated area was probably due to FA pollution over a long period because chromium content was found more in FA (189.33±5.13 mg/kg).

Ferrous: Ferrous (Fe) exhibits both deficiencies and toxicity to the human body. Ferrous is also an essential trace element found readily in soil. This study revealed that the amount of Fe (mg/kg) in the FCS samples of different stations of the KTPS surrounding area ranged from 33866.66±503.32 mg/kg (FCS2) to 51733.33±602.77 mg/kg (FCS4) with an average value of 42172.21±7979.45 mg/kg (Table 1). Ferrous content in FCS3 and FCS4 samples exceeded the permissible limit of 50000 mg/kg proposed by WHO, 2007 (Table 2). The average value of Fe concentration of the KTPS area was quite higher than the control (32833.33 ±305.50 mg/kg) and FA (26166.66±115.47 mg/kg). Such mode of result could be due to FA accumulation throughout the area for a long period as well as excessive use of chemical fertilizers, pesticides, weedicides, and insecticides during cultivation[31].

The high content of all the assessed heavy metals (Pb, As, Cr, and Fe) indicated that the soil in the vicinity of the KTPS was polluted due to the overflow of FA from the fly ash ponds during the rainy season, disperse of the pollutants by air flow and irrigation of the cultivated land using FA contaminated water of the Rupnarayana river and the adjacent canal[19,20].

Table 2
Permissible limits for heavy metals in soils prescribed by different organizations.

Organizations	Heavy Metals (mg/kg DW)			
	Lead (Pb)	Arsenic (As)	Chromium (Cr)	Ferrous (Fe)
WHO/FAO (1996, 2001, 2007)[7,14,15]	100 (2001 and 2007)	12 (1996)	100 (1996), 50 (2001), 5-30 (2007)	50000 (2007)
Indian Standard[10]	250-500	NA	NA	NA
European standard[10,16]	300	NA	150	NA
Dutch Standards[25]	85	NA	100	NA
Finnish Standard (MEF-2007) threshold value and lower guideline value, respectively[33]	60 and 200	5 and 50	100 and 200	NA

NA = Not applicable, MEF- Ministry of Environment of Finland, WHO = World Health Organization.

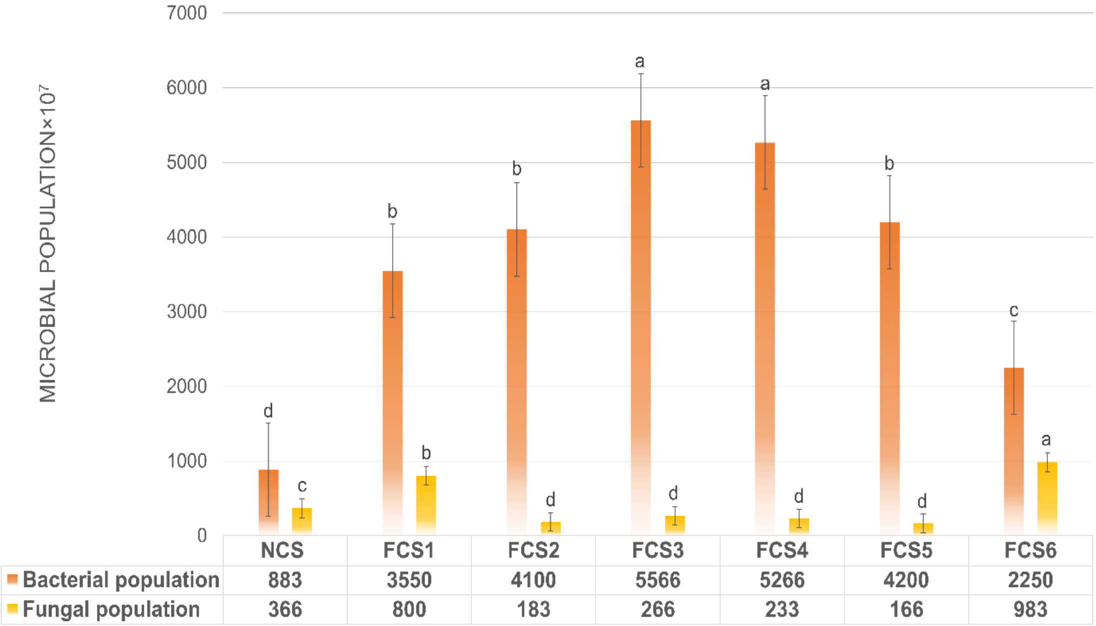

Figure 4: Bar graph showing colony forming unit (CFU) of bacteria and fungi comparatively in the collected control soil sample (NCS) and fly ash-contaminated soil samples (FCS) of KTPS surrounding areas. Different letters indicate statistically significant variations ($p < 0.05$) based on Duncan's multiple comparison test and bars represent the standard error (± SE).

Microbial load: Microbial activity indicates the health of the soil. As per the aims of the study, the bacterial and fungal load in the fly ash-contaminated soil collected from the six stations (viz. Kharisha, Katchora, Mandar Gachha, Baragechhe, Amalhanda, and Denachara) surrounding the KTPS are estimated with graphical representations in figure 4.

Bacterial Load: In the study, the lowest number of bacteria was observed in the FCS6 [(2250±100.00) $\times 10^7$ CFU/gm)] which was collected from the Denachara station. On the other hand, the highest number of bacteria was observed in the FCS3 [(5566.66±617.11) $\times 10^7$ CFU/gm], which was collected from the Mandar Gachha area. Both the values are higher than the bacterial population of NCS [(883.33±76.37) $\times 10^7$ CFU/gm] which was collected from Jia Khali of Purba Medinipur, WB, about 25 km away from KTPS. Hence, the gradual increase of bacterial load has been observed as NCS (883.33$\times 10^7$) <FCS6 (2250$\times 10^7$) <FCS1 (3550$\times 10^7$) <FCS2 (4100$\times 10^7$) <FCS5 (4200$\times 10^7$) <FCS4 (5266$\times 10^{7)}$ <FCS3 (5566.66$\times 10^7$). When compared to control soil, fly ash-contaminated soil in the KTPS surrounding areas showed an increase in the bacterial population along with an improvement in reproductive potential.

Fungal load: On the other hand, the lowest number of fungal load was estimated in the FCS5 [(166.66±28.86) $\times 10^7$ CFU/gm] which was collected from the Amalhanda area whereas highest number of fungi was found in FCS6 [(983.33±76.37) $\times 10^7$ CFU/gm]. Hence the gradual increasing of fungal load has been observed as- FCS5 (166.66$\times 10^7$) <FCS2 (183.33$\times 10^7$) <FCS4 (233.33$\times 10^7$) <FCS3 (266.66$\times 10^7$) <NCS (366.66$\times 10^7$) <FCS1 (800$\times 10^7$) <FCS6 (983.33$\times 10^7$). Fungal load was observed higher in FCS1 and FCS6 but lower in FCS5, FCS2, FCS3, FCS4 compared with NCS. The comparative impact of fly ash on bacterial and fungal growth is shown in figure 4.

In this study, the overall results were the same flow as the previous one[34] which also depicted that FA addition could be beneficial to motivate the soil microbiota including enzymatic activities which in turn promoted the productivity of soil. The previous study also showed that a higher percentage of FA could upgrade heavy metal concentration in which stressed microbial growth deteriorated. Soils that have more organic matter are supposed to have more microorganisms[4], but this result was not always seen because the growth of microbes in the soil was not controlled only by organic matter.

The growth of microorganisms in the soil depends on the pH of the soil, the concentration of various heavy metals presents in the soil, and their nature of toxicity including microbial species. It was shown that a higher fly ash content reduced the overall number of bacterial and fungal species[28]. Increased FA dosages caused metal contamination which had detrimental impacts on soil microbial populations and associated enzymatic function. Therefore, lower FA dosages could be used to improve the soil's microbiota, which is crucial for supporting plant growth[34]. The mode of result regarding microbial flora of the studied area was probably due to a certain level of FA contamination that was still under tolerance.

Conclusion

The findings of this study reveal significant alterations in the physico-chemical and microbial properties of soils surrounding the KTPS (West Bengal, India) highlighting the environmental consequences of fly ash deposition. Elevated levels of heavy metals and disrupted nutrient balance were observed, indicating some detrimental impacts of fly ash on soil quality. It was also found that bacterial activity was higher in all of the FCS samples, as fungal activity was enhanced in FCS1 and FCS6 of the KTPS area concerning control. The mode of result regarding microbial flora of the studied area was probably due to a certain level of FA contamination that was still under tolerance. In some of the FCS samples, fungal activity was less, which revealed that heterogeny of metal stress with variable concentration due to diffuse accumulation of fly ash could negatively impact the fungal growth.

Additionally, the adverse effects on microbial diversity and activity underscore the long-term implications for soil health and agricultural productivity. These changes in soil properties not only compromise the fertility of the affected lands but also pose potential risks to local ecosystems and human health through the bioaccumulation of toxic elements. The study highlights the critical need for sustainable strategies for fly ash management to mitigate its adverse effects and also to support environmental restoration in the regions impacted by fly ash deposition. Protecting soil health is vital for ensuring the sustainability of agriculture and maintaining the ecological balance in regions impacted by thermal power plant emissions.

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