# **The Application of Fly Ash Soil Amendment Technology (FASAT) in Forestry and Plantations: A Comprehensive Analysis of Efficacy, Environmental Risk, and Strategic Implementation**

**Executive Summary**

Coal fly ash, a voluminous and hazardous byproduct of thermal power generation, presents a profound environmental management challenge globally. This report provides an exhaustive analysis of its use as a soil amendment in forestry and plantation settings, with a particular focus on the Fly Ash Soil Amendment Technology (FASAT) framework developed in India. The analysis reveals a stark duality: fly ash is both a potentially valuable soil conditioner and a significant environmental contaminant.

Its primary benefits are physical. The fine, silt-like texture of fly ash can ameliorate the properties of degraded soils by improving water-holding capacity, reducing bulk density, enhancing porosity, and altering permeability. Its typically alkaline nature allows it to function as an effective liming agent, neutralizing acidic soils common in degraded landscapes and mine spoils. When applied at carefully controlled, low-to-moderate rates (generally below 25% by weight), fly ash has been shown in numerous studies to enhance the growth and biomass of various forestry species, with results sometimes on par with conventional chemical fertilizers.

However, these benefits are inextricably linked to severe and non-trivial risks. The principal hazard stems from its chemical composition. Fly ash concentrates an array of potentially toxic heavy metals from the parent coal, including lead, arsenic, cadmium, chromium, and mercury. Improper management, particularly through traditional disposal in unlined ash ponds, has led to documented cases of severe groundwater contamination in India, with metal concentrations far exceeding safe drinking water standards. When applied to land, these metals pose a long-term risk of leaching into aquifers or bioaccumulating in plants, thereby entering the food web and threatening ecosystem and human health. The initial safety conferred by the high pH of the ash, which immobilizes metals, may be temporary, as natural ecological processes can re-acidify the soil over decades, potentially releasing a latent pool of contaminants.

The regulatory framework in India, driven by the Ministry of Environment, Forest and Climate Change (MoEF&CC), mandates 100% utilization of fly ash, creating a powerful incentive for thermal power plants to find outlets for this material. While agriculture and forestry are permitted uses, this report argues that a purely quantitative utilization target risks overshadowing the critical need for qualitative safety and rigorous, site-specific risk assessment.

This report concludes that the use of fly ash in forestry is a high-risk, high-reward strategy that is not universally applicable. It should not be considered a conventional fertilizer but a potent industrial soil conditioner best suited for large-scale reclamation of severely degraded, low-risk sites. Its application demands a high degree of technical precision and must be guided by the precautionary principle. The most viable path forward involves an integrated soil management approach, where fly ash is used in conjunction with organic amendments to leverage its physical benefits while mitigating its chemical risks. The recommendations advocate for a policy shift towards qualitative safety standards, mandatory site-specific risk assessments, and robust long-term monitoring to ensure that the pursuit of waste utilization does not create a legacy of environmental contamination.

## **Section 1: The Physicochemical Profile of Coal Fly Ash**

A comprehensive understanding of the application of fly ash in any environmental context, particularly in complex ecosystems like forests, must begin with a fundamental characterization of the material itself. Its origin, classification, and intricate chemical and physical makeup dictate its behavior in soil, its interaction with plant life, and its potential as both a resource and a hazard.

### **1.1 Genesis and Classification**

Fly ash is the fine particulate residue that results from the combustion of pulverized coal in thermal power plants.1 Inside the furnace of a power boiler, where temperatures reach approximately 1500°C, the non-combustible inorganic mineral components of the coal, such as quartz, calcite, and clay minerals, melt into tiny molten droplets.2 These droplets are carried out of the combustion chamber with the exhaust or flue gases.2 As they cool, they solidify into small, spherical, glassy particles. This material is then captured from the flue gas stream by pollution control equipment, most commonly electrostatic precipitators, baghouses, or mechanical cyclone separators, to prevent its release into the atmosphere.3

The proportion of fly ash generated relative to coarser bottom ash (which is collected at the bottom of the boiler) depends significantly on the type of furnace technology employed. Dry-bottom boilers, a common type, can convert about 80% of the total ash into fly ash. In contrast, wet-bottom (or slag-tap) furnaces retain up to 50% of the ash as slag, with the remainder becoming fly ash. Cyclone furnaces, which use crushed coal, retain as much as 70-80% of the ash as boiler slag, producing only 20-30% fly ash.3 This distinction is relevant for understanding the total volume of fine particulate waste that a given power plant must manage.

For technical and commercial purposes, fly ash is primarily classified according to the American Society for Testing and Materials (ASTM) C 618 standard. This standard differentiates fly ash into two main classes based on the type of coal from which it was derived, which in turn dictates its chemical composition and reactive properties.1

* **Class F Fly Ash:** This class is produced from the burning of harder, older coals, specifically anthracite and bituminous coal.2 Its defining characteristic is a low concentration of lime (calcium oxide,  
  CaO), typically less than 15%.2 Chemically, it is rich in alumina (  
  Al2​O3​) and silica (SiO2​).4 Due to its low lime content, Class F fly ash is not self-hardening. However, it exhibits pozzolanic properties, meaning that in the presence of water, its glassy silica and alumina particles will react with a source of calcium hydroxide (lime) to form stable, cementitious compounds chemically similar to those in hydrated Portland cement.2 Class F is the more abundant type of fly ash produced globally.2
* **Class C Fly Ash:** This class originates from younger coals, namely lignite or sub-bituminous coal.2 It is characterized by a much higher concentration of lime, often exceeding 15% and sometimes reaching as high as 30%.2 This high lime content makes Class C fly ash both pozzolanic and cementitious (self-hardening). It can react directly with water to form hardened compounds without an external source of lime.1 This property makes it valuable in applications where higher early strength is required, such as in structural concrete.1

This classification is of paramount importance for forestry and agricultural applications. The higher lime content of Class C ash gives it a superior ability to neutralize acidic soils. However, its self-hardening nature can also lead to soil compaction or the formation of hardpan layers if not managed correctly. Conversely, the pozzolanic nature of Class F ash means its reactivity in soil is more dependent on the existing soil chemistry, particularly the presence of free lime.

### **1.2 Chemical Composition**

The bulk chemical composition of fly ash is dominated by a few key oxides that reflect the mineralogy of the parent coal. The primary constituents are silicon dioxide (SiO2​), aluminum oxide (Al2​O3​), ferric oxide (Fe2​O3​), and calcium oxide (CaO).1 Together, the elements Si, Al, Fe, Ca, and Mg typically account for more than 85% of the total mass of most fly ashes.5 The ASTM C 618 standard uses these oxides for its classification scheme: Class F fly ash must have a minimum combined percentage of

SiO2​, Al2​O3​, and Fe2​O3​ of 70%, while Class C ash is defined by its higher CaO content, often greater than 20%.2

Beyond these major oxides, fly ash contains smaller quantities of magnesium oxide (MgO), potassium oxide (K2​O), sodium oxide (Na2​O), sulfur trioxide (SO3​), and titanium dioxide (TiO2​).6 The pH of fly ash is highly variable, ranging from acidic (pH 4.5) to strongly alkaline (pH 12.0).7 This variability is largely determined by the sulfur content of the parent coal and the balance of acidic versus basic oxides in the ash. Fly ash with a high calcium-to-sulfur molar ratio is typically alkaline, while ash with a low ratio can be acidic.8 Most fly ash produced in India, where coals are generally low in sulfur but high in alkaline earth metals, is alkaline in nature.7

The physical appearance of fly ash can also provide clues to its composition. A tan or light color often indicates a high lime content, characteristic of Class C ash. A brownish hue is typically associated with a higher iron oxide content. A dark gray to black color is usually attributed to a high level of unburned carbon, which is measured as Loss on Ignition (LOI).2

### **1.3 Physical Characteristics**

The physical nature of fly ash particles is fundamental to its utility as a soil amendment. It is a fine, powdery material composed predominantly of microscopic, spherical, glass-like particles.1 The particle size distribution is generally similar to that of silt, with a majority of particles having a diameter of less than 0.010 mm.8 A significant fraction of these particles can be in the

PM2.5​ range (less than 2.5 micrometers in diameter), which has profound implications for air quality and human health.13

This fine, silty texture is the primary reason for its ability to modify soil physical properties.14 Key physical characteristics include:

* **Low Bulk Density:** Fly ash typically has a bulk density of less than 1.0 g/cm3, which is considerably lower than most mineral soils.7 This property allows it to reduce the density of heavy, compacted soils.
* **High Surface Area:** The fine, porous nature of the particles gives fly ash a high specific surface area.9
* **High Water-Holding Capacity (WHC):** As a result of its fine texture and high surface area, fly ash can hold a significant amount of water, with reported WHC values ranging from 43% to 66% by weight.7 This is one of its most valuable properties for amending coarse, sandy soils.
* **Pozzolanic Activity:** As previously noted, this property allows fly ash to form cementitious compounds.2 While this is a major benefit in the concrete industry, in a soil context, it can contribute to the formation of hardened layers or soil compaction, particularly with Class C ash and at high application rates.15

### **1.4 Trace Elements and Heavy Metals: The Inherent Hazard**

The single greatest concern and barrier to the widespread, unregulated use of fly ash in any environmental application is its content of trace elements, particularly toxic heavy metals. The high-temperature combustion process concentrates the inorganic trace constituents present in the parent coal into the resulting ash.1 Consequently, fly ash is recognized as a hazardous byproduct by regulatory bodies like the U.S. Environmental Protection Agency (EPA).1

Fly ash contains a wide suite of potentially toxic elements, including **arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), selenium (Se), nickel (Ni), vanadium (V), boron (B), and zinc (Zn)**.1 The concentrations of these metals are highly variable and depend on the geology of the coal source, but they can be present at levels that pose a significant risk to environmental and human health. For instance, a study of Indian fly ash found concentrations of lead up to 34.8 ppm, nickel at 51.6 ppm, chromium at 64.7 ppm, and manganese at 286.2 ppm.21 Mercury content, while often lower, can reach levels of 1 ppm.19 These elements may exist as discrete, fine mineral particles or as deposits on the surface of the larger glassy spheres, a factor that influences their solubility and potential to leach into the environment.6 The presence of this toxic cocktail is the central element of the risk-benefit equation for fly ash utilization and dictates the need for stringent control and management.

**Table 1: Comparative Physicochemical Profile of Class F and Class C Fly Ash**

| Property | Class F Fly Ash | Class C Fly Ash | Significance for Forestry Application |
| --- | --- | --- | --- |
| **Parent Coal** | Anthracite, Bituminous | Lignite, Sub-bituminous | Determines the fundamental chemical makeup of the ash. |
| **Key Oxides** | SiO2​+Al2​O3​+Fe2​O3​≥70% | Lower sum of these oxides | Class F is more silica-alumina based; Class C has a more balanced profile with calcium. |
| **Lime (CaO) Content** | Low (<15%) | High (>15%, often >20%) | High CaO in Class C provides superior and faster neutralization of acidic forest soils. |
| **Pozzolanic/Cementitious** | Pozzolanic (requires lime to set) | Pozzolanic and Cementitious (self-hardening) | Class C's self-hardening property may increase risk of soil compaction or hardpan formation. |
| **Typical pH** | Can be acidic or alkaline | Typically alkaline | Most fly ash available for land application, especially in India, is alkaline, making it suitable for acid soil reclamation. |
| **Primary Benefits** | Improves soil texture, water retention; slow reaction can be more manageable. | Rapid pH correction; provides Ca as a nutrient; improves soil physical properties. | Both classes can improve poor physical soil structure, a key goal in reclamation forestry. |
| **Primary Risks** | Potential heavy metal leaching; may require lime addition for full reactivity. | Higher risk of over-liming (raising pH too high); potential for soil compaction; heavy metal leaching. | The primary risk for both is the potential for heavy metal contamination of soil and water. |

Data compiled from sources: 1

The characterization of fly ash reveals a fundamental paradox that frames the entire discussion of its use. On one hand, it is explicitly classified as a hazardous waste due to its chemical composition, particularly the presence of toxic heavy metals.1 On the other hand, it is promoted as a valuable resource material and even an "environment saviour" because its bulk physicochemical properties allow it to replace virgin materials like cement in construction or to ameliorate degraded soils.1 This is not a contradiction but a reflection of its dual nature. The challenge of fly ash management is therefore not to deny one aspect in favor of the other, but to develop strategies that leverage its beneficial resource properties while rigorously controlling and mitigating its inherent hazardous characteristics.

This challenge is particularly acute in the context of India, the birthplace of the FASAT concept. Indian coal is known for its exceptionally high ash content, typically ranging from 30-45%, in stark contrast to the 10-15% ash content of many internationally traded coals.8 The direct consequence of this is that for every unit of energy produced, Indian thermal power plants generate a disproportionately massive volume of fly ash. This magnifies the scale of the disposal problem to immense proportions, making the need for bulk utilization solutions like land application in forestry and agriculture far more urgent than in many other nations. It also means that any environmental impact, whether positive or negative, is amplified simply due to the sheer quantity of material that must be managed, raising the stakes for getting the application right.

## **Section 2: Fly Ash as a Soil Amendment: Mechanisms and Effects**

The potential of fly ash as a tool for land reclamation and forestry is rooted in its ability to fundamentally alter the physical, chemical, and biological properties of soil. Understanding the mechanisms behind these changes is crucial for predicting its effects, optimizing its application, and mitigating its risks. The impact of fly ash is not monolithic; it is a complex interplay of its inherent characteristics and the baseline conditions of the soil to which it is applied.

### **2.1 Impact on Soil Physical Properties**

The most consistent and widely documented benefits of fly ash application are related to the improvement of soil physical structure. Its fine, silty particle size and low density make it a powerful physical conditioner, especially for soils at the extremes of the textural spectrum.

* **Texture Modification:** Fly ash's particle size distribution is predominantly in the silt and fine sand range, giving it a silt-loam texture.12 When added to soil, it can permanently alter the native texture. In coarse-textured sandy or rocky soils, the addition of these finer particles fills pore spaces, which leads to improved soil aggregation, better infiltration control, and significantly increased water retention.15 Studies have shown that application rates as high as 70 tonnes per hectare (t/ha) can be sufficient to formally change a soil's textural classification, for example, from a sandy soil to a more productive loamy soil.26 At very high rates (up to 75%), it can completely redefine the soil's sand, silt, and clay fractions.15
* **Bulk Density and Porosity:** Due to its low specific gravity and bulk density (often less than 1.0 g/cm3), fly ash is highly effective at reducing the bulk density of heavy, compacted soils such as clays.7 The incorporation of this lighter material physically separates the dense soil particles, leading to a significant increase in total porosity. This creates more space for air and water, improves soil workability, and facilitates easier root penetration for plants.26 Research has documented reductions in soil density on the order of 15-20% and increases in porosity from 43% to 53% with fly ash amendments, which are substantial structural improvements.26
* **Water-Holding Capacity (WHC):** Perhaps the most significant physical benefit, especially for forestry in arid or degraded landscapes, is the dramatic increase in WHC. The fine particles of fly ash increase the soil's microporosity, creating a vast network of small pores that can hold water against the force of gravity, making it available to plant roots for longer periods.26 This is particularly transformative for sandy soils, which are notoriously poor at retaining moisture. One study documented that an application of 40 t/ha of fly ash increased the maximum WHC to over 35% 7, while another found that a 40% amendment increased WHC from 39% to 55%.26 This improved moisture retention is highly beneficial for plant establishment and survival, especially in rain-fed agricultural and forestry systems.26
* **Permeability (Hydraulic Conductivity):** The effect of fly ash on permeability is dependent on the initial soil type. In heavy clay soils, which often suffer from poor drainage, fly ash improves structure and aggregation, thereby increasing permeability and allowing water to move more freely through the profile. One study showed an increase in permeability in a clay loam from 0.54 cm/hr to 2.14 cm/hr with a 50% fly ash addition.26 Conversely, in excessively drained sandy soils, the fine particles of fly ash clog the large pore spaces, reducing the hydraulic conductivity and slowing the rate of water loss. The same study found that in a sandy soil, permeability decreased from 23.80 cm/hr to 9.67 cm/hr, effectively helping the soil to retain water.26

### **2.2 Impact on Soil Chemical Properties**

The chemical effects of fly ash are more complex and present a mixture of benefits and risks. While it can correct certain chemical imbalances, it can also introduce new ones.

* **pH Neutralization:** A primary chemical benefit of most fly ash, particularly the alkaline types common in India (pH 6-11), is its ability to act as a liming agent.7 When applied to acidic soils, the high concentration of basic oxides, especially calcium oxide (  
  CaO), and alkaline carbonates results in a neutralization reaction. These compounds release hydroxide ions (OH−) or consume hydrogen ions (H+) from the soil solution, thereby raising the soil pH.7 Field experiments have demonstrated that an application of 40 t/ha can raise the pH of an acidic soil to a near-neutral level of 6.38, creating a more favorable environment for many plant species and improving the availability of certain nutrients.7
* **Nutrient Supply:** Fly ash is often touted as a source of plant nutrients, but its profile is highly imbalanced and should not be mistaken for a complete fertilizer.7
  + **Deficient in Nitrogen and Phosphorus:** Fly ash contains virtually no nitrogen (N), as this element is volatilized and lost during the high-temperature combustion process.27 It is also typically low in plant-available phosphorus (P).7 Furthermore, the high pH environment created by alkaline fly ash, along with its high concentrations of aluminum (Al) and iron (Fe), can exacerbate phosphorus deficiency by causing soluble phosphate to precipitate into insoluble compounds that are unavailable for plant uptake.7
  + **Source of Secondary and Micronutrients:** The true nutritional value of fly ash lies in its role as a rich source of essential secondary nutrients and micronutrients. It contains significant amounts of potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S).7 It also supplies a wide array of micronutrients that are often deficient in degraded soils, including boron (B), molybdenum (Mo), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu).7
* **Electrical Conductivity (EC):** A notable chemical risk is the increase in soil electrical conductivity, or salinity. Fly ash contains a variety of soluble salts, and its application invariably increases the EC of the soil.29 While low levels of increase may be harmless, high application rates can raise salinity to levels that are detrimental to plant growth by inducing osmotic stress.

### **2.3 Impact on Soil Biological Properties**

The soil microbiome is a critical component of a healthy ecosystem, and the impact of fly ash on it is a crucial consideration. The effects are complex and highly dependent on the application rate and the presence of other soil amendments.

* **Ambiguous Effects on Microbial Communities:** At low to moderate application rates, fly ash can indirectly stimulate microbial activity. By improving soil physical conditions (better aeration and moisture) and neutralizing acidity, it can create a more hospitable environment for beneficial soil microorganisms.12 However, at high application rates, the extreme pH, high salinity, and presence of toxic heavy metals can have a strong negative effect, suppressing microbial populations and inhibiting critical enzymatic processes.12 One study specifically noted that fly ash addition in a nursery setting decreased soil dehydrogenase activity, a key indicator of microbial metabolic function.31
* **Lack of Organic Matter:** A fundamental limitation of fly ash is that it is an entirely mineral, inorganic material. It does not contain the organic matter necessary to initiate humus formation and other crucial soil-forming processes.32 Organic matter is the primary food source for most soil organisms and is essential for building a stable, resilient, and biologically active soil ecosystem. Therefore, fly ash alone cannot support the development of a healthy soil food web.

The analysis of these effects reveals a clear pattern: the primary, most reliable benefits of fly ash application are physical, while the primary risks and limitations are chemical and biological. This suggests that the ideal use case for fly ash is in situations where severe physical limitations—such as extreme texture (sand), compaction, or poor water retention—are the main barriers to plant growth. It is less suited for soils that are already physically adequate but are limited by chemical deficiencies, especially in nitrogen or phosphorus.

This dichotomy also underscores the essential role of organic matter in successful fly ash application. Several studies indicate that the efficacy and safety of fly ash are significantly enhanced when it is used in conjunction with organic amendments like farmyard manure (FYM) or compost.12 Organic matter addresses the key deficiencies of fly ash: it supplies the missing nitrogen and a carbon-based energy source for microbes, it can buffer against the extreme pH of the ash, and its organic acids can chelate (bind to) heavy metals, reducing their bioavailability and toxicity. This strong synergistic relationship implies that fly ash should not be viewed as a standalone solution. Instead, its application, particularly under a framework like FASAT, should be conceived as one component within a broader Integrated Soil Fertility Management system. The technology's success is likely codependent on the co-application of organic matter, a factor that has profound implications for application methodology, cost-benefit analysis, and regulatory guidance.

**Table 2: Summary of Fly Ash Effects on Soil Physical, Chemical, and Biological Properties**

| Soil Property | Effect of Fly Ash Application | Mechanism | Key Benefits for Forestry | Key Risks/Drawbacks |
| --- | --- | --- | --- | --- |
| **Texture** | Alters texture towards silt loam | Addition of fine, silt-sized particles | Improves structure of very sandy or very clayey soils. | At high rates, can create dust issues; potential for surface crusting. |
| **Bulk Density** | Decreases in dense soils | Low specific gravity of ash particles physically separates soil particles. | Improves root penetration, aeration, and workability in compacted soils. | May not be beneficial in already light, low-density soils. |
| **Water-Holding Capacity (WHC)** | Significantly increases | Increases microporosity due to fine particle size. | Crucial for sapling survival and growth in drought-prone or sandy soils. | Can lead to waterlogging in poorly drained soils if permeability is also reduced. |
| **Permeability** | Increases in clays; Decreases in sands | Improves aggregation in clays; clogs large pores in sands. | Improves drainage in heavy soils; reduces water loss in coarse soils. | Potential for creating perched water tables if a compacted layer forms. |
| **pH** | Increases pH of acidic soils | Release of alkaline oxides (e.g., CaO, MgO) neutralizes H+ ions. | Corrects soil acidity, improving nutrient availability and reducing Al toxicity. | Risk of over-liming (pH > 8.5), which can induce micronutrient deficiencies. |
| **Nutrient Availability** | Supplies K, Ca, Mg, S, and micronutrients; Deficient in N and available P. | Ash is a mineral source of nutrients but N is volatilized and P can be fixed. | Provides a slow-release source of many essential elements except N. | Cannot support plant growth alone due to N deficiency; can induce P deficiency. |
| **Electrical Conductivity (EC)** | Increases | Addition of soluble salts present in the ash. | None. | High application rates can increase soil salinity to toxic levels for plants. |
| **Microbial Activity** | Variable: can stimulate or inhibit | Improved physical conditions can help; high pH and heavy metals can harm. | At low doses with organics, can create a better habitat for microbes. | High doses are toxic to many soil microorganisms; lacks organic carbon as a food source. |

Data compiled from sources: 7

## **Section 3: Application in Forestry and Plantation Ecosystems: Case Studies and Growth Impact**

Moving from the fundamental science of soil-ash interactions to applied practice, this section evaluates the real-world performance of fly ash as an amendment in forestry and plantation settings. The analysis synthesizes results from nursery trials, field studies, and long-term ecological experiments to determine the effects on tree survival, biomass accumulation, and overall ecosystem development.

### **3.1 FASAT: A Strategic Framework for Land Reclamation in India**

The concept of using fly ash in agriculture and forestry is not new, but it has been formalized and promoted in India under the banner of Fly Ash Soil Amendment Technology (FASAT). This framework was developed by India's Central Fuel Research Institute (CFRI) following over a decade of large-scale field demonstration studies.34 The explicit goal of FASAT is to enable the sustainable, bulk utilization of the country's massive stocks of fly ash and pond ash for the productive reclamation of degraded lands.34 This includes agricultural lands, problematic soils (e.g., acidic, saline), mine spoils, and abandoned ash ponds themselves.

Within the FASAT framework, fly ash is positioned as a versatile, multi-purpose agent capable of acting as 34:

* A **soil conditioner** to improve physical properties.
* A **source of in-situ plant nutrients**.
* A **liming agent** to neutralize acidity.
* A **fertilizer additive** to enhance the efficacy of other inputs.

While the specific, proprietary protocols of FASAT are not publicly detailed in the available research, its guiding principles align with the broader scientific findings on fly ash application. It represents a strategic, government-backed effort to transform a massive waste stream into a tool for ecological restoration and enhanced productivity, with reported yield increases of 20-60% for various crops and significant growth improvements for forestry species.34

### **3.2 Effects on Sapling Survival, Biomass, and Yield**

The response of plants to fly ash is highly sensitive to the application rate, exhibiting a distinct non-linear pattern that is crucial for any successful application.

A comprehensive meta-analysis of 85 studies synthesized the overall effect of fly ash on plant growth. While the aggregate result showed a net decrease in plant biomass by 15.2%, this top-line figure is misleading as it averages across all application rates.35 A more granular analysis revealed a critical dose-dependent response:

* At **low application rates** (defined as <25% of soil mass by weight), fly ash application **enhanced plant biomass by 11.6% to 29.2%**.
* At **high application rates** (50-100% of soil mass), fly ash application caused a severe **decrease in biomass by 45.8%**.35

This establishes a clear pattern: there is a beneficial window of application, beyond which fly ash becomes toxic and detrimental to plant growth. This finding is corroborated by numerous individual case studies in forestry and agriculture.

**Forestry Case Studies:**

* **Indian Pulpwood Species:** In field trials conducted on degraded soils in India, a mix of 18-24% fly ash by volume (v/v) with soil resulted in a 10% increase in the growth of key pulpwood species: *Eucalyptus tereticornis*, *Acacia auriculiformis*, and *Casuarina equisetifolia*. Notably, this growth enhancement was on par with the results from standard chemical fertilizer treatments, highlighting its potential as a low-cost alternative.31
* ***Populus deltoides* (Poplar):** A nursery study on poplar saplings found that an application rate of 20% fly ash by weight (w/w) was optimal for overall biomass production. The biomass of stems and roots continued to increase up to this 20% level. However, the biomass of leaves and, consequently, the total plant biomass, peaked at a lower rate of 10% fly ash.36 This suggests that different parts of the plant may have different tolerance thresholds.
* ***Leucaena leucocephala*:** Research on this nitrogen-fixing tree, which is widely used for land reclamation, found that a 20% (w/w) fly ash mixture was optimal for seed germination, but a higher rate of 40% (w/w) was most effective for promoting subsequent seedling growth and quality.37
* **General Indian Forestry Trials:** Other experiments in India with species such as *Tectona grandis* (Teak) and *Acacia* have reported growth increases of 20-30% compared to controls.38 Some of these studies noted the best results when soil was mixed with ash in a 1:1 ratio (50% ash).38 This result appears to contradict the findings of the broader meta-analysis 35, which showed negative effects at such high rates. This discrepancy underscores the high degree of variability in outcomes based on the specific ash type, soil conditions, and plant species tolerance, reinforcing the need for site-specific testing rather than relying on a single universal rate.

Micronutrient Uptake Dynamics:

The study on Populus deltoides also provided critical insights into nutrient uptake. While the fly ash amendment substantially enriched the soil with micronutrients like iron (Fe), manganese (Mn), and zinc (Zn), the plant's ability to absorb them was complex. The bioconcentration factor (a measure of uptake from soil to plant tissue) for all three micronutrients peaked at a 10% fly ash application rate and then declined sharply as the rate increased to 20%.36 This indicates that the higher soil pH created by the larger volume of alkaline ash began to impede the uptake of these metals, making them less bioavailable to the plant even though their total concentration in the soil was higher. This demonstrates that simply adding nutrients to the soil does not guarantee they will be available to the plant; the chemical environment created by the amendment is paramount.

### **3.3 Application Rates and Methodologies**

The collective evidence from various studies makes it clear that there is no single, universally "correct" application rate for fly ash. Successful and beneficial applications have been reported across a range, from low percentages of 5-10% by weight, to moderate levels of 20-40% (w/w), corresponding to field application rates of approximately 70-180 t/ha.26 The consensus from a wide body of research is that rates exceeding the 25-40% threshold often cross into a toxicological danger zone, leading to reduced growth, nutrient imbalances, and potential heavy metal toxicity.28 The guiding principle must be site-specific experimentation to identify the optimal dose for a given soil, climate, and target tree species.27

In terms of application methodology for large-scale forestry or reclamation projects, fly ash is typically handled like other bulk soil materials. It can be spread and leveled using standard earth-moving equipment such as dozers or graders, usually in loose lifts of 150 to 300 mm thickness.14 It is then incorporated into the native soil, often through deep ploughing to ensure thorough mixing and prevent the formation of distinct, potentially impermeable layers.14 During this process, moisture control is a critical operational consideration. The ash must be sufficiently conditioned with water to prevent the generation of hazardous airborne dust, but not so wet as to become unworkable slurry.14 In nursery settings, the methodology is simpler, with fly ash being used as a measured component of the potting mixture for raising seedlings.31

While specific FASAT application protocols are not detailed, the principles of modern, rapid afforestation techniques, such as the Miyawaki Method, could provide a valuable framework for integrating fly ash into forestry projects. This approach, which aims to create dense, biodiverse, native forests quickly, could be adapted as follows:

1. **Soil Preparation:** Instead of just surface application, the soil would be thoroughly excavated and amended to a depth of at least one meter. This would involve mixing the native soil with the pre-determined optimal dose of fly ash and, crucially, a significant quantity of locally sourced organic matter (e.g., compost, manure) to provide the missing nitrogen and biological components.40
2. **Species Selection:** A dense and diverse mix of native tree and shrub species, representing all layers of a natural forest (canopy, tree, sub-tree, shrub), would be selected based on the area's Potential Natural Vegetation (PNV).40
3. **Dense Planting:** Saplings would be planted at a very high density, typically 3 to 5 plants per square meter. This intense competition for light forces rapid upward growth, accelerating the establishment of a forest canopy.42
4. **Post-Planting Care:** The entire area would be heavily mulched with materials like straw to retain the high moisture content of the amended soil, regulate soil temperature, and suppress weed growth. The site would require active maintenance, including watering and weeding, for the first 2-3 years, after which the dense, rapidly growing forest becomes self-sustaining.40

Integrating fly ash into such a system could leverage its physical benefits to create an ideal initial growth medium, while the method's emphasis on organic matter and biodiversity could help mitigate the associated chemical risks.

### **3.4 Long-Term Ecological Succession (43-Year Coniferous Forest Study)**

Short-term studies provide valuable data on initial growth, but a landmark 43-year study on a coniferous forest amended with large doses of fly ash offers critical, irreplaceable insights into the long-term ecological consequences.38 This experiment revealed that the ecosystem's response to fly ash is not static but highly dynamic.

* **Soil pH Dynamics: Initial Alkalization, Eventual Re-acidification:** The initial application of alkaline fly ash dramatically increased the pH of the native acidic Podzol soils. However, over the 43-year period, a new ecological process began to dominate. The accumulation and decomposition of organic matter (leaf and needle litter) from the established forest gradually led to the re-acidification of the upper soil horizons. This demonstrates that natural soil-forming processes can, over a long timescale, begin to counteract and even reverse the initial chemical shock of the amendment.38
* **Nutrient Cycling:** This pH shift had direct consequences for nutrient availability. The macronutrient content (P, K, Mg) in the soil, which had initially increased in proportion to the ash dose, began to decline over time. This was attributed to a combination of continuous plant uptake and increased leaching as the soil became more acidic and water moved more freely through the developing organic horizons.38
* **Plant Community Evolution:** The changes in soil chemistry drove a profound shift in the plant community. The overall habitat transformed from a coniferous forest type to a mixed forest type. More specifically, the herbaceous understory underwent a clear succession. Initially, the high-pH environment favored calcicole (lime-loving) plant species. As the soil re-acidified over the decades, these species disappeared and were replaced by calcifuge (acid-loving) species characteristic of the original coniferous forest ecosystem.38 This provides powerful evidence that the plant community dynamically tracks the long-term chemical evolution of the amended soil.
* **Tree Survival and Natural Selection:** The long-term results also highlighted the role of natural selection. Pioneer tree species that are tolerant of poor soil conditions and high light, such as *Pinus* (pine) and *Larix* (larch), survived and thrived. In contrast, some of the planted deciduous species with higher nutrient requirements failed to persist. A remarkable finding was the spontaneous colonization and eventual dominance of *Tilia cordata* (small-leaved lime) in the plot with the highest ash dose. This species, which was not planted, is adapted to the rich, alkaline conditions created by the ash and outcompeted the other trees. This shows that over time, natural succession will favor species that are best adapted to the novel, human-modified soil environment.38

The findings from these applied studies reveal two critical overarching principles. First, the concept of an "optimal dose" is paramount. The plant response to fly ash follows a non-linear, parabolic curve where benefits increase up to a specific threshold (often in the 10-25% range) and then rapidly decline into toxicity.28 This means that "more is not better," and the application of fly ash requires a high degree of scientific precision. A seemingly small error in calculation or uneven field application could easily push a project from the beneficial side of the curve to the detrimental side, resulting in crop failure and land degradation. This elevates the technical expertise required for successful implementation and underscores the significant risk of failure if the process is not managed with extreme care.

Second, the long-term ecological dynamics can reverse the initial effects of the application. The 43-year study powerfully demonstrates that the dramatic chemical changes induced by fly ash are not static.38 Natural processes, particularly the accumulation of forest litter, can trigger a new, long-term ecological trajectory, including the re-acidification of the soil. This implies that using fly ash is not a one-time, permanent fix. Managers cannot simply apply the material and walk away; they must understand that the ecosystem will continue to evolve, potentially in unexpected ways that could, for example, re-mobilize heavy metals that were initially locked up by the high pH. This has major implications for the necessity of long-term monitoring and the development of adaptive management strategies.

**Table 3: Case Studies on Fly Ash Application in Forestry and Agriculture**

| Plant Species | Soil Type/Condition | Application Rate (% or t/ha) | Key Findings on Growth/Yield | Key Findings on Soil/Nutrient Uptake | Source Snippet(s) |
| --- | --- | --- | --- | --- | --- |
| *Populus deltoides* (Poplar) | Nursery Potting Mix | 0, 5, 10, 20, 30% (w/w) | Optimal biomass at 20%. Stem/root biomass increased up to 20%; leaf/total biomass peaked at 10%. | Micronutrient (Fe, Mn, Zn) uptake peaked at 10% and then declined due to rising pH. | 36 |
| *Eucalyptus*, *Acacia*, *Casuarina* | Degraded Soils (India) | 18-24% (v/v) | 10% growth increase, on par with chemical fertilizer treatment. | Nursery trials showed improved biomass at 10-20% but decreased soil dehydrogenase activity. | 31 |
| *Leucaena leucocephala* | Forest Soil (India) | 0, 20, 40, 60, 80, 100% (w/w) | Optimal germination at 20%; optimal seedling growth and quality at 40%. | Higher rates increased soil pH, EC, and available P and K. | 37 |
| *Tectona*, *Acacia*, etc. | Forest Plantations (India) | 1:1 ratio with soil (50%) | 20-30% higher growth compared to controls without ash. | Not specified. | 38 |
| Beetroot | Field Soil (Pot Study) | 0, 5, 10, 15, 20, 25% (w/w) | Significantly higher plant growth, pigment content, protein, and carbohydrates at 15% ash. | Not specified. | 33 |
| Wheat | Decade and Sandy Soils | Up to 30% ash + 10% compost | Improved germination, plant height, and grain yield. | Improved soil texture, structure, and bulk density. | 26 |
| Rice and Peanut | Acid Lateritic Soil | Not specified | Ample scope for augmenting yield in combination with chemical fertilizer. | Improved soil fertility; can save on chemical fertilizer use. | 39 |
| General Plant Biomass | Meta-analysis of 85 studies | 0-100% | Biomass enhanced by 11.6-29.2% at <25% ash; decreased by 45.8% at 50-100% ash. | Element concentrations in plants increased with ash application rate. | 35 |

Data compiled from sources: 26

## **Section 4: Environmental Risk Assessment and Mitigation**

While fly ash offers potential benefits as a soil conditioner, these must be rigorously weighed against its significant and well-documented environmental hazards. Its classification as a hazardous waste is not arbitrary; it is based on its inherent potential to contaminate soil, water, and air, and to introduce toxic substances into the ecosystem and human food chain. A comprehensive risk assessment is therefore a non-negotiable prerequisite for any responsible consideration of its use in forestry.

### **4.1 Heavy Metal Leaching and Groundwater Contamination**

The single most severe environmental threat posed by fly ash is the leaching of heavy metals and other pollutants into groundwater. This risk is realized when water, typically from rainfall, percolates through fly ash deposits, whether in large disposal sites or in soils amended with the material. The water dissolves soluble components, including toxic metals, and carries them downward into underlying soil strata and, eventually, into groundwater aquifers.21

The conventional method of fly ash disposal in many parts of the world, particularly in India, involves mixing it with water to form a slurry and pumping it into vast, often unlined, "ash ponds".21 This practice creates a perfect scenario for contamination. The constant presence of water ensures that soluble toxic elements are continuously leached out, and the lack of an impermeable liner allows this contaminated leachate to seep directly into the ground.21 The leaching potential is exacerbated in such open systems due to seasonal variations in temperature and moisture, which can alter the chemical reactions governing metal solubility.21 The catastrophic failure of ash dykes, which has occurred in India, can lead to the sudden and devastating release of millions of tons of toxic slurry into surrounding agricultural lands and rivers.47

Empirical evidence from India paints a grim picture of the consequences. Studies of groundwater quality in the vicinity of thermal power plant ash ponds have revealed alarming levels of heavy metal contamination, with concentrations frequently exceeding the permissible limits for safe drinking water set by the World Health Organization (WHO).21 One such study found the following concentrations in groundwater near an ash pond, demonstrating the scale of the threat:

* **Lead (Pb):** Ranged from 0.17 to 0.581 parts per million (ppm), vastly exceeding the WHO limit of 0.01 ppm.
* **Nickel (Ni):** Ranged from 0.024 to 0.087 ppm, with the upper value being more than four times the WHO limit of 0.02 ppm.
* **Chromium (Cr):** Ranged from 0.036 to 0.061 ppm, with over half the samples exceeding the WHO limit of 0.05 ppm.
* **Iron (Fe):** Ranged from 0.186 to an extremely high 11.98 ppm, far above the WHO limit of 0.3 ppm.

Other toxic metals of significant concern that are known to be present in Indian fly ash and have the potential to leach into soil and water include **Cadmium (Cd), Arsenic (As), and Manganese (Mn)**.46 This direct, quantifiable evidence of severe groundwater pollution from existing fly ash disposal sites serves as a critical cautionary tale for any proposed large-scale land application.

### **4.2 Bioaccumulation and Food Chain Contamination**

The danger of heavy metals does not end with groundwater contamination. Metals that are leached into the soil can be taken up by the roots of plants, including trees in a forestry setting.13 This process, known as bioaccumulation, introduces these toxic substances into the base of the terrestrial food web.

Once in the plant, metals can accumulate in various tissues, including roots, stems, and leaves.13 While this poses an obvious and direct threat in agricultural systems where crops are consumed by humans, the risk in forestry ecosystems is also profound. Herbivores, from insects to deer, consume the contaminated plant matter. As these herbivores are consumed by carnivores, the heavy metals are transferred and become progressively more concentrated at each successive trophic level. This process, known as biomagnification, can lead to toxic concentrations of metals in apex predators, disrupting reproductive cycles, causing illness, and ultimately leading to a loss of biodiversity and overall ecosystem instability.13

Furthermore, heavy metals are persistent. Unlike organic pollutants, they do not biodegrade. Once introduced into a soil system, they can remain for decades or even centuries, creating a long-term legacy of pollution that is extraordinarily difficult and expensive to remediate.13

### **4.3 Airborne Particulate Matter and Associated Health Risks**

The physical nature of fly ash—its fine, powdery, and lightweight consistency—makes it highly susceptible to wind erosion, particularly when handled or stored in a dry state.13 This generates airborne dust, a significant source of air pollution with direct human health consequences.

The primary concern is the presence of fine and ultra-fine particulates (PM2.5​ and smaller). Because of their microscopic size, these particles can be inhaled deep into the human respiratory system, bypassing the body's natural defenses and reaching the sensitive alveolar regions of the lungs.13 Chronic exposure to such particulate matter is strongly linked to a range of adverse health outcomes, including cardiovascular disease, bronchitis, and other respiratory illnesses.13

A specific and severe risk associated with fly ash dust is **silicosis**, an incurable and progressive fibrotic lung disease caused by the inhalation of crystalline silica.13 Crystalline silica is a known component of many fly ashes and is classified as a known human carcinogen.19 For communities living in the vicinity of thermal power plants or large ash disposal sites, long-term exposure to fly ash dust has been linked to a disturbing array of health problems, including hypertension, kidney disease, reproductive problems, and various forms of cancer.20

### **4.4 Risk Mitigation Strategies**

Given the severity of these risks, the application of fly ash in forestry must be governed by a robust set of mitigation strategies designed to minimize environmental harm. These strategies must be implemented at every stage of the process.

* **Pre-Application Assessment:** Before any application, a rigorous and independent analysis of both the fly ash and the target site is essential. The fly ash must be chemically characterized to determine its specific heavy metal content and pH.8 The soil must be tested for its baseline pH, texture, organic matter content, and any pre-existing contamination. A hydrogeological survey should be conducted to assess the depth of the water table and the permeability of the soil to evaluate leaching risk.
* **Strict Dose Control:** As established in Section 3, the line between beneficial and toxic is thin. It is critical to adhere strictly to scientifically determined, site-specific optimal application rates, which are generally below 25% by weight, to avoid crossing the toxicity threshold.35
* **Mandatory Co-application of Organic Matter:** The use of fly ash in conjunction with high-quality organic amendments like compost or manure should be considered a standard and non-negotiable practice. Organic matter can help immobilize heavy metals through chelation, buffer the soil against extreme pH shifts, supply the nitrogen that fly ash lacks, and foster a healthy microbial community that contributes to overall ecosystem resilience.12
* **Phytostabilization and Species Selection:** In a forestry context, the trees themselves can be part of the mitigation strategy. The goal of phytostabilization is to use plants to reduce the mobility of contaminants in the soil. This can involve selecting tree species that are known to tolerate high levels of certain metals and effectively "lock" them into their woody biomass for the long term, preventing them from leaching or being cycled through leaf litter.37
* **Strategic Site Selection:** Fly ash application should be prohibited in high-risk areas. This includes sites near sensitive aquifers, surface water bodies (lakes, rivers), wetlands, or on highly permeable sandy soils where the risk of rapid leaching is greatest.46 The ideal sites are those that are highly degraded and located in geologically stable, low-risk areas.
* **Comprehensive Long-Term Monitoring:** An application of fly ash cannot be a "fire and forget" operation. It necessitates the implementation of a robust, multi-decade monitoring program. This program must track changes in soil chemistry (pH, EC, heavy metals), groundwater quality in nearby monitoring wells, and the concentration of heavy metals in plant tissues to ensure that contaminants are not migrating into the wider environment.27

A critical consideration in this risk assessment is the temporary nature of metal immobilization. A key argument for the safety of fly ash application is that its inherent alkalinity raises soil pH, which in turn causes most heavy metals to precipitate into solid, non-bioavailable forms.49 However, the 43-year forestry study provides a crucial counterpoint, showing that forest ecosystems can naturally re-acidify soil over long periods through the decomposition of organic litter.38 A subsequent decrease in soil pH could re-mobilize these previously sequestered heavy metals, potentially creating a "ticking time bomb" scenario where a latent contamination problem emerges decades after the initial application. This possibility reinforces the absolute necessity of a long-term perspective and continuous monitoring in any fly ash land application project.

Finally, it is essential to frame the risk of land application within the context of existing disposal practices. The severe and ongoing groundwater contamination documented in India is a direct result of unsafe disposal in unlined ash ponds.21 This means that the push for utilization technologies like FASAT is driven not only by the desire to find a productive use for a waste material but also by the urgent need to cease a demonstrably harmful and polluting disposal method. The debate is therefore not about finding a "zero-risk" option, as one does not exist. It is about choosing the "lesser risk" and developing the scientific, technical, and regulatory capacity to manage that risk effectively.

**Table 4: Heavy Metal Concentrations in Indian Fly Ash and Contaminated Groundwater vs. Safety Limits**

| Heavy Metal | Concentration in Fly Ash (ppm) | Observed Concentration in Groundwater near Ash Ponds (ppm) | WHO Permissible Limit for Drinking Water (ppm) | Risk Factor (Observed/Limit) |
| --- | --- | --- | --- | --- |
| **Lead (Pb)** | 34.8 | 0.170 – 0.581 | 0.01 | 17x – 58x |
| **Nickel (Ni)** | 51.6 | 0.024 – 0.087 | 0.02 | 1.2x – 4.4x |
| **Chromium (Cr)** | 64.8 | 0.036 – 0.061 | 0.05 | 0.7x – 1.2x |
| **Iron (Fe)** | 2635.0 | 0.186 – 11.98 | 0.3 | 0.6x – 40x |
| **Manganese (Mn)** | 286.2 | 0.013 – 0.178 | 0.1 | 0.1x – 1.8x |
| **Cadmium (Cd)** | Variable | Variable, but a known component | 0.003 | Not Quantified |
| **Arsenic (As)** | Variable | Variable, but a known component | 0.01 | Not Quantified |

Data compiled from a study on heavy metal contamination near an Indian thermal power plant ash pond.21 The "Risk Factor" is calculated by dividing the maximum observed groundwater concentration by the WHO limit and indicates how many times the safety standard was exceeded.

## **Section 5: Regulatory Framework and Economic Considerations in India**

The application of fly ash in forestry cannot be understood in a vacuum; it is deeply embedded within a specific regulatory and economic context, particularly in India, where the scale of generation is immense and government policy has been a primary driver of utilization efforts. The legal mandates and financial incentives in place shape the decisions of both the producers (thermal power plants) and potential users (forestry and plantation managers).

### **5.1 The MoEF&CC Fly Ash Utilization Mandate**

The central pillar of India's fly ash management strategy is a series of notifications issued by the Ministry of Environment, Forest and Climate Change (MoEF&CC). Beginning with a foundational notification in 1999, this regulatory framework has been progressively strengthened and amended, with the most recent comprehensive version issued in December 2021 and further amended in 2022 and 2024.56

The core of this mandate is an unambiguous requirement for **100% utilization of all ash** (both fly ash and bottom ash) generated by coal or lignite-based thermal power plants (TPPs).58 This target is to be achieved over a rolling three-year cycle, with a stipulation that in any single year of the cycle, utilization must not fall below 80%.58 This creates a powerful, legally binding impetus for TPPs to actively seek out and supply ash to various user industries.

The notification explicitly lists the "eco-friendly purposes" for which fly ash can be utilized. This list includes conventional uses such as manufacturing cement, bricks, blocks, and tiles; construction of roads and embankments; and filling of abandoned mine voids.60 Critically for the scope of this report, the list also explicitly permits the use of fly ash in

**"agriculture, to be conducted in a controlled manner based on soil testing"**.58 This provision gives legal sanction to frameworks like FASAT, positioning land application as a legitimate and encouraged method of utilization.

Furthermore, the regulations address the enormous quantities of "legacy ash"—the unutilized ash that has accumulated in ash ponds over decades. The 2021 notification sets an ambitious target for the complete utilization of all legacy ash within a ten-year timeframe, commencing from April 2022.58 This dual focus on managing both current generation and historical accumulation places immense pressure on the entire system to find large-scale, bulk uses for fly ash, with forestry and land reclamation being prime candidates.

### **5.2 CPCB Guidelines and Enforcement**

The Central Pollution Control Board (CPCB) is designated as the primary enforcement and monitoring authority for these regulations, alongside the respective State Pollution Control Boards (SPCBs).58 The CPCB's role is to translate the broad mandates of the MoEF&CC notification into practical guidelines and to ensure compliance. This includes developing technical specifications for the safe design and operation of ash ponds, creating standard operating procedures for various utilization pathways, and managing a national web portal to provide real-time data on ash availability from different TPPs for the benefit of potential users.58

The most potent tool in the CPCB's enforcement arsenal is the imposition of **environmental compensation** for non-compliance. Under the 2021 notification, if a TPP fails to meet its utilization targets, it is liable to pay a significant fine of **₹1000 per ton** on the unutilized quantity of ash.58 This financial penalty fundamentally changes the economic calculation for TPPs. It transforms fly ash from a zero-cost waste product into a significant financial liability, creating a powerful economic incentive to ensure it is lifted and utilized by other agencies rather than being sent to a landfill or ash pond.

### **5.3 Economic Analysis: A Cost-Benefit Perspective**

The economics of using fly ash in forestry are complex, involving direct costs, avoided costs, and significant potential externalities that are often difficult to quantify.

**Benefits and Cost Savings:**

* **For Thermal Power Plants (TPPs):** The primary economic driver for TPPs is cost avoidance. By facilitating the utilization of their ash, they avoid two major costs: the direct operational cost of disposal in ash ponds (estimated at around ₹100 per ton) and, more significantly, the potential environmental compensation fine of ₹1000 per ton for non-compliance.58 A cost-benefit analysis for a single proposed Ash Utilization Park in India projected a staggering saving of ₹600 Crores (approximately USD 72 million) over a 20-year period from avoided disposal costs alone.62
* **For Farmers and Forestry Managers:** A cornerstone of the Indian policy is the mandate for TPPs to provide **fly ash free of cost to farmers** and other users within a 300 km radius.8 This represents a direct and substantial saving on the input costs for soil amendments. For a large-scale afforestation or land reclamation project, where hundreds or thousands of tons of material might be needed, this zero acquisition cost is a powerful incentive.
* **Increased Productivity:** As demonstrated by case studies, the correct application of fly ash can lead to tangible increases in biomass and crop yields.28 This translates directly to higher revenue for the plantation or farm, improving the overall benefit-cost ratio of the operation. One study on blackgram found that an integrated application including fly ash resulted in a significantly higher benefit-cost ratio (2.41) compared to controls.33

**Costs and Economic Risks:**

* **Application and Transportation Costs:** While the fly ash itself may be free, it is not costless to use. The user must bear the costs of transportation from the TPP to the site, as well as the operational costs of spreading the material and incorporating it into the soil.63 For large-scale projects, these logistical costs can be substantial.
* **Monitoring and Testing Costs:** Responsible use of fly ash necessitates significant investment in scientific analysis. The costs of pre-application laboratory testing of the ash and soil, and particularly the costs of a long-term environmental monitoring program for groundwater and plant tissues, represent a significant and ongoing financial commitment that must be factored into any project budget.33
* **Cost of Co-Amendments:** As the evidence strongly suggests that fly ash is most effective and safest when used with organic matter, the cost of purchasing and applying compost or manure must also be included in the total economic calculation.12 This can significantly alter the cost-effectiveness compared to using fly ash alone.
* **Long-Term Environmental Liability:** The most significant and often overlooked economic risk is the potential for long-term environmental damage. The cost of remediating a contaminated aquifer or soil system can be astronomically high, representing a massive financial liability that could fall on the landowner or the state for generations.13 This potential future cost is a major externality that is rarely captured in initial project-level cost-benefit analyses.

The Indian regulatory landscape clearly demonstrates that government mandates are the primary force driving fly ash utilization. The 100% utilization target, backed by severe financial penalties, creates immense pressure on TPPs to find outlets for their ash through any approved means.56 However, this creates a potential "perverse incentive." The intense focus on achieving a quantitative utilization target could inadvertently overshadow the need for qualitative safety. There is a risk that the pressure to simply get rid of the ash could lead to its application in unsuitable locations or without the necessary rigorous, site-specific risk assessments. This highlights a critical need for policy to evolve beyond a simple percentage target to incorporate more nuanced criteria for what constitutes safe and appropriate utilization.

Similarly, the policy of providing "free" fly ash to farmers and foresters is a powerful economic lever, but it can be misleading by masking significant downstream costs.8 A true economic analysis must consider the Total Cost of Ownership (TCO) over the project's entire lifecycle. This includes not just the zero acquisition cost, but also the costs of transportation, application, necessary co-amendments like compost, and, most importantly, the long-term investment required for monitoring and the potential financial liability of environmental remediation.63 Presenting fly ash as simply "free" without this broader context could encourage improper and unsafe use by stakeholders who are not equipped to manage the associated costs and risks.

## **Section 6: Comparative Analysis with Conventional Soil Amendments**

To fully appreciate the unique profile of fly ash as a soil management tool, it is essential to compare its properties, benefits, and risks against those of conventional amendments used in forestry and agriculture, namely organic amendments (compost, manure) and chemical fertilizers. This comparative context reveals that fly ash is not a direct substitute for either but rather a distinct tool with a specific, and limited, set of applications.

### **6.1 Fly Ash vs. Organic Amendments (Compost, Manure)**

Fly ash and organic amendments like compost and manure represent fundamentally different approaches to soil improvement.

* **Nutrient Profile and Primary Function:** Fly ash is an inorganic, mineral-based amendment. Its primary nutritional contribution is a suite of minerals, including potassium (K), calcium (Ca), magnesium (Mg), and various micronutrients. However, it is critically deficient in the two most important macronutrients for plant growth: nitrogen (N) and organic matter.7 In contrast, compost and manure are rich in both organic matter and nitrogen, providing a more balanced, albeit slower-releasing, source of comprehensive plant nutrition.64 The primary function of fly ash is as a physical conditioner and chemical liming agent.15 The primary function of compost is as a biological and structural agent, feeding the soil microbiome, building stable soil aggregates, and enhancing long-term fertility through the creation of humus.64
* **Mechanism of Action:** Fly ash achieves its effects through physical alteration (changing texture and WHC) and direct chemical reactions (neutralizing acidity).15 Compost works through biological decomposition. As microbes break down the organic matter, they release nutrients slowly and steadily, build soil structure, and create a thriving ecosystem that can suppress diseases and cycle nutrients efficiently.64
* **Associated Risks:** The principal risk associated with fly ash is chemical toxicity from its inherent content of heavy metals.17 The risks associated with improperly managed compost or manure are typically biological (potential for pathogens if not fully composted) or related to nutrient runoff (e.g., excess phosphorus), but they do not carry the same intrinsic risk of persistent heavy metal contamination.64
* **Synergistic Potential:** The differing profiles of fly ash and organic amendments make them highly complementary. When used together, each can mitigate the weaknesses of the other. Compost provides the essential nitrogen and organic carbon that fly ash lacks. It fosters a healthy microbial community that can be harmed by high doses of ash alone. Crucially, the organic acids and humus in compost can help to chelate or bind to the heavy metals in fly ash, reducing their bioavailability and locking them into more stable forms in the soil.12 This synergy strongly suggests that an integrated approach is superior to using either amendment in isolation.

### **6.2 Fly Ash vs. Chemical Fertilizers**

The comparison between fly ash and synthetic chemical fertilizers highlights the difference between soil conditioning and direct plant feeding.

* **Nutrient Delivery:** Chemical fertilizers are designed to provide a rapid, targeted, and concentrated dose of the primary macronutrients (N-P-K) in a readily available form for immediate plant uptake.64 Fly ash, conversely, provides a much broader spectrum of secondary nutrients (Ca, Mg, S) and micronutrients, but it delivers them in a less concentrated, slower-release form as the ash particles weather over time. Most importantly, it cannot supply the nitrogen that is the primary driver of vegetative growth provided by most fertilizers.7
* **Impact on Soil Health:** The long-term, repeated use of chemical fertilizers, particularly in the absence of organic matter inputs, can degrade overall soil health. It can lead to the depletion of soil organic matter, disrupt the balance of the soil microbiome, and contribute to soil acidification.64 Fly ash, when applied correctly, has the opposite effect on pH (it neutralizes acidity) and can improve the physical health of the soil (structure, WHC). However, it carries its own set of chemical risks, including potential heavy metal contamination, pH overshoot, and increased salinity.15
* **Cost Profile:** In India, under the current regulatory regime, fly ash is often available to farmers and foresters at zero cost, whereas chemical fertilizers represent a significant and recurring operational expense.8 Studies have shown that the use of fly ash can reduce the need for certain fertilizers (especially those supplying K, Ca, or Mg) and can increase the overall efficiency of the fertilizers that are applied, leading to tangible cost savings.39

### **6.3 Integrated Soil Management: The Synergistic Potential**

The comparative analysis makes it clear that fly ash should not be viewed as a one-to-one replacement for either organic amendments or chemical fertilizers. Each has a distinct role, and they are not interchangeable. The most effective and sustainable approach to land reclamation and forestry nutrition involves leveraging the strengths of all three within an integrated soil management system.12

An optimal strategy, particularly for reclaiming severely degraded land for afforestation, could look like this:

1. **Foundation Setting with Fly Ash:** A one-time, carefully calculated application of fly ash to correct fundamental physical problems (e.g., poor texture, low WHC) and chemical problems (e.g., extreme acidity).
2. **Building Fertility with Organic Matter:** The foundational application of fly ash would be combined with an initial large application and subsequent regular applications of compost or manure. This builds the soil's organic matter content, establishes a healthy microbial ecosystem, and provides a slow-release source of nitrogen.
3. **Targeted Nutrition with Chemical Fertilizers:** Chemical fertilizers would be used sparingly and only as needed to address specific, diagnosed nutrient deficiencies that cannot be met by the other amendments, based on regular soil and plant tissue testing.

This integrated approach uses fly ash for what it does best—bulk physical and chemical conditioning—while using organic matter to provide the biological life and nitrogen it lacks, and to mitigate its chemical risks. It relegates chemical fertilizers to a supplemental, precision role, reducing their overuse and negative long-term impacts.

This analysis leads to a crucial clarification of terminology and strategy. While fly ash contains some plant nutrients, its primary function and value lie in its ability to fundamentally alter the physical and chemical properties of the soil matrix itself.16 It is, therefore, more accurately described as a

**"soil conditioner"** or **"soil ameliorant"** rather than a "fertilizer." This distinction is critical for managing expectations and designing effective application strategies. Treating fly ash like a conventional fertilizer will inevitably lead to failure due to nitrogen deficiency and potential nutrient imbalances. It must be treated as a specialized tool for foundational soil reclamation, upon which a proper, long-term fertility program—based on organic matter and supplemented by fertilizers—can be built.

Furthermore, the economic case for using fly ash is strongest when it is viewed as a substitute for other materials that are used in bulk. The most significant and quantifiable cost savings come from replacing other expensive bulk materials: landfill space for TPPs, agricultural lime for acid soil reclamation, and virgin topsoil or fill material for large-scale land reclamation projects like mine spoil rehabilitation.33 This implies that the economic viability of FASAT and similar approaches is highest in the context of major reclamation and afforestation projects on severely degraded lands, where it can substitute for these costly bulk materials. Its economic case as a simple, routine fertilizer replacement in established, healthy forests or agricultural systems is considerably weaker.

**Table 5: Comparative Analysis of Soil Amendments for Forestry**

| Feature | Coal Fly Ash | Organic Amendments (Compost/Manure) | Chemical Fertilizers |
| --- | --- | --- | --- |
| **Primary Function** | Physical conditioner; Liming agent | Biological activator; Fertility builder | Direct plant nutrition |
| **Nutrient Profile** | Rich in K, Ca, Mg, S, micronutrients; Deficient in N and available P. | Balanced profile; Rich in N and organic matter; Slow-release nutrients. | Concentrated N-P-K; Targeted formulas. |
| **Impact on Soil Structure** | High (improves texture, porosity, WHC) | High (improves aggregation, builds humus) | Low to Negative (can degrade structure over time) |
| **Impact on Soil Biology** | Negative at high doses; Lacks organic carbon | High (provides food for microbes, increases diversity) | Negative (can harm microbial communities) |
| **Nutrient Release Speed** | Slow to Medium (weathering-dependent) | Slow and steady (decomposition-dependent) | Fast and immediate |
| **Primary Risks** | Heavy metal toxicity; High pH/salinity; P-fixation; Potential compaction. | Pathogens (if uncomposted); Nutrient runoff; Weed seeds. | Nutrient leaching; Water pollution; Soil acidification; Salt buildup. |
| **Cost Profile** | Low to zero acquisition cost; High testing and monitoring costs. | Moderate to high cost, depending on source and transport. | High and recurring cost. |
| **Best Use Case** | One-time application for foundational reclamation of physically poor, acidic soils. | Regular application for long-term fertility building and maintaining soil health. | Targeted, supplemental application to correct specific, acute nutrient deficiencies. |

Data compiled from sources: 7

## **Conclusion and Strategic Recommendations**

The use of coal fly ash in forestry and plantation settings presents one of the most compelling and complex environmental paradoxes of our time. It is a voluminous industrial byproduct, laden with hazardous materials, that simultaneously possesses the potential to heal our most degraded landscapes. This analysis confirms that fly ash is not a panacea, nor is it an unmanageable evil. It is a potent, high-risk, high-reward tool whose application demands scientific precision, regulatory rigor, and an unwavering commitment to the precautionary principle.

The evidence is clear: at low-to-moderate, carefully controlled doses, fly ash can significantly improve the physical properties of poor soils, neutralize acidity, and enhance tree growth. However, applied incorrectly or in the wrong context, it poses a severe and persistent threat of chemical toxicity, with the potential to contaminate groundwater with heavy metals like lead and arsenic and to introduce these toxins into the food web. The success of any land application project hinges on navigating this narrow window between benefit and harm.

Based on this comprehensive analysis, the following strategic recommendations are proposed for policymakers, forestry managers, and researchers.

### **Recommendations for Policy Makers (e.g., MoEF&CC, CPCB)**

1. **Evolve from Quantitative to Qualitative Utilization Targets:** The current mandate for 100% utilization, while effective at driving action, should be refined. Policy must evolve beyond a simple percentage target to include robust criteria for *safe and appropriate* utilization. This could involve developing a risk-based classification system that restricts or prohibits application in high-risk zones (e.g., near aquifers, on highly permeable soils) and requires a higher standard of proof for safety in all land applications. The goal should not be just to "use" 100% of the ash, but to ensure every ton utilized contributes to a net environmental benefit.
2. **Mandate Comprehensive, Site-Specific Risk Assessments:** Before any permit for land application of fly ash is granted, a mandatory, independent Environmental Impact Assessment (EIA) must be required. This EIA should not be a cursory check but a detailed scientific investigation including: (a) full chemical analysis of the specific ash batch for heavy metals and radioactivity; (b) comprehensive baseline analysis of the target soil's physical and chemical properties; (c) a thorough hydrogeological assessment to map groundwater flow and vulnerability; and (d) fate and transport modeling to predict the long-term movement of potential contaminants.
3. **Establish and Fund a National Long-Term Monitoring Program:** The "ticking time bomb" potential of heavy metal re-mobilization due to long-term soil acidification necessitates a national commitment to long-term monitoring. A program should be established, funded by the environmental compensation fines collected from non-compliant TPPs, to systematically monitor existing land application sites across India. This program would track soil chemistry, groundwater quality, and heavy metal uptake in vegetation over multi-decade timescales to build a robust, real-world dataset on the long-term impacts of fly ash in different Indian ecosystems.
4. **Strengthen and Mandate Guidelines for Integrated Application:** The scientific consensus points to the synergy between fly ash and organic matter. Policy and guidelines should reflect this by officially recommending, and in high-risk scenarios mandating, the co-application of fly ash with certified-quality organic amendments like compost. This integrated approach should be recognized as the best practice for mitigating risks and improving efficacy.

### **Recommendations for Forestry and Plantation Managers**

1. **Adopt the Precautionary Principle:** Fly ash must be treated as a potent but hazardous industrial chemical, not as a benign fertilizer. The burden of proof for demonstrating the safety and efficacy of its use in a specific project must lie squarely with the project proponent. If there is any doubt about the safety or long-term consequences, the application should not proceed.
2. **"Test, Don't Guess":** Never apply fly ash without commissioning a comprehensive, third-party laboratory analysis of both the specific ash batch being supplied and the target soil. This data is the essential foundation for any responsible decision-making and for calculating a safe and effective application rate.
3. **Prioritize High-Need, Low-Risk Sites:** The ideal use case for fly ash is not on healthy, productive land. Its application should be prioritized for the reclamation of severely degraded, acidic, and physically poor soils, such as abandoned mine spoils or barren wastelands. These sites should be geographically located far from sensitive groundwater resources, surface water bodies, and human settlements to minimize the consequence of any potential failure.
4. **Conduct On-Site Pilot Trials:** Before committing to a large-scale application, conduct small-scale pilot trials on the target site. Use a range of application rates (e.g., 0%, 5%, 10%, 15%, 20%) on small plots planted with the intended tree species. Monitor these plots for at least one full growing season to determine the site-specific optimal dose and to observe any unforeseen negative effects on local flora and soil conditions.
5. **Integrate, Don't Isolate:** Do not use fly ash as a standalone amendment. Always design its application as part of a holistic, integrated soil management plan. This plan must include the co-application of organic matter (compost, manure) to supply nitrogen, buffer pH, and help immobilize contaminants.

### **Future Research Directions**

Despite decades of study, critical knowledge gaps remain. Future research should prioritize the following areas:

* **Long-Term Fate and Transport of Heavy Metals:** There is a pressing need for more multi-decade studies, similar to the 43-year experiment, but specifically on Indian soil types and under various climatic conditions, to understand the long-term fate, transport, and bioavailability of heavy metals from fly ash.
* **Identification of Native Phytoremediation Species:** Research should focus on identifying and breeding native Indian tree and plant species that are particularly effective at either hyper-accumulating or phytostabilizing the specific heavy metals of concern in Indian fly ash.
* **Development of Low-Cost Monitoring Technologies:** To make long-term monitoring economically feasible, research is needed to develop and deploy low-cost, real-time sensors and field kits for monitoring heavy metal leaching from amended sites.
* **Comprehensive Lifecycle Economic Analysis:** A nationwide economic study is required to compare the full lifecycle costs and benefits of FASAT versus other reclamation strategies. This analysis must include the monetization of environmental externalities, such as the long-term cost of potential groundwater remediation, to provide a true picture of its economic viability.

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