Effects of thermal power plant ash on germination and growth of containerized *Pinus pinea* seedlings

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Abstract. The present study provides a novel perspective on the use of thermal power plant waste, an issue of growing importance for environmental sustainability and waste management. Specifically, it examines the effects of incorporating different proportions of thermal power plant ash (TPPA) into growing media on the germination and early development of containerized 1+0 stone pine (*Pinus pinea*) seedlings.
The aim was to assess TPPA's impact on germination percentage (GP), mean germination time (MGT), seedling morphology, and biomass accumulation. Six media types were prepared: 100% conventional media, 100% sand, 5%, 15%, and 30% TPPA mixed with sand, and 100% TPPA.
The highest GP (81%) was observed in the 5% TPPA + 95% sand mix, declining to 54% with increasing TPPA content. Significant differences were found in most morphological traits, except for stem biomass, and the ratios of needle, above-ground, and root biomass to total biomass. Seedlings grown in the 5% TPPA + 95% sand mix showed the greatest seedling height and root length. Nitrogen content and the C/N ratio in needles varied significantly. The highest needle nitrogen was found in the 30% TPPA + 70% sand and 100% TPPA media, while the highest root nitrogen content was recorded in the 100% TPPA media.
These results suggest that TPPA, particularly at low concentrations, can support healthy seedling development and may serve as a beneficial soil amendment in nurseries. Utilizing TPPA as a growing media component could offer a sustainable approach to recycling industrial waste in seedling production.

Keywords: ash; biomass; fertilizer; inorganic amendment; sustainable; waste.

1. Introduction

Coal has remained one of the primary sources used in electricity generation. Approximately 35% of this production is supplied by coal-fired thermal power plants (Gilewska et al., 2020; Kaczmarek et al., 2021; Wiatros-Motyka et al., 2024). In Türkiye, the share of coal in electricity generation has continued to increase. In 2023, 36.3% of the 326.3 billion kilowatt-hours of electricity produced came from coal-fired thermal power plants, compared to 34.6% in 2022 and 31.4% in 2021 (Enerjigunlugu, 2023). Akgül and Yoncacı (2021) indicate that the utilization rate of fly ash in Türkiye is quite low: According to Turkish Statistical Institute data from 2018, 87.5% (22.8 million tons) of the total 26.1 million tons of waste generated by thermal power plants was disposed of in ash hills, ash dams, or regulated storage facilities; only 12.4% (2.8 million tons) was sent to licensed waste processing facilities and used in the backfilling of mines, while 0.1% was disposed of using other methods.

The accelerated process of industrialization, in conjunction with mounting energy requirements, has resulted in the substantial utilization of coal-fired power plants. These facilities, in turn, generate copious amounts of combustion by-products, chief among them being fly ash. The management and disposal of fly ash has been identified as a significant environmental concern, with associated risks including air, soil, and water contamination. Consequently, the identification of sustainable and effective utilization methods for this by-product has become a crucial area of research.

Coal-fired power stations are responsible for the production of substantial quantities of fly ash, and the storage and disposal of this environmental threat have become a significant ecological concern worldwide (Mathapati et al., 2022; Szadek et al., 2023). The extraction, processing, and utilization of natural resources can lead to environmental issues such as air, soil, and water pollution, ecosystem degradation or destruction, and a decline in biodiversity (Ramesh et al., 2024). The proper management of waste and such a large quantity of fly ash poses a significant challenge in terms of pollution, with potential threats to air, water, and soil (Rawat et al., 2018; Szadek et al., 2023).

The role of coal-fired thermal power plants in global electricity generation is a significant topic of discussion. The combustion of coal in the generation of electricity results in the generation of significant quantities of thermal power plant ash (TPPA). The inherent volatility of TPPA leads to its dispersal, resulting in water, soil, and air contamination. The management of this by-product necessitates substantial spatial requirements for storage. The utilization of TPPA as a plant additive in diverse growth environments has been a subject of numerous experimental endeavors.

Zhai et al., (2021) stated that the use of biomass for energy is increasing rapidly, and consequently, the significance of the resulting ash is also growing. On a global scale, the combustion of biomass from various sources currently generates 170 Mt (megaton = 10^6 tons) of ash per year, with the potential to reach approximately 1000 Mt per year. Nonetheless, it has been established that approximately 40% of fly ash produced on a global scale remains unused (Delić et al., 2022).

As Andrae (2020) asserted, the global primary energy consumption is projected to rise in this decade. It is estimated that there are approximately 0.7 million hectares of stone pine-dominated forests in the region surrounding the Mediterranean basin (Mutke et al., 2012). The stone pine has been employed for a variety of purposes, including but not limited to environmental restoration, watershed and soil conservation, dune stabilization, and urban afforestation. (Boydak and Çalışkan, 2015, 2021; Çalışkan and Boydak, 2017; Mutke et al., 2012). In addition to the diverse purposes for which stone pine has been utilised throughout history, it is most notable for its edible kernels. These kernels have been a food source for humans since the Paleolithic era, owing to their high nutritional value (Evaristo et al., 2010).
Yu et al., (2019) stated that while thermal power plant ash contains various toxic elements, it also has nutrient content and can be used as a soil amendment due to its biomass growth-promoting properties. Fly ash, a major problematic solid waste globally, poses a significant environmental threat due to restrictions on its storage and disposal in thermal power plants (Gajić et al., 2018; Panda et al., 2020). A particularly promising application of fly ash is its potential use as a medium for the cultivation of plant seedlings. Fly ash has been found to be rich in essential minerals such as calcium, magnesium, and potassium, which are known to be beneficial for plant growth. Nevertheless, the utilization of fly ash as a medium for plant cultivation is contingent upon various factors, including its chemical composition, pH levels, and the presence of potentially hazardous heavy metals. As defined by Gilewska et al., (2020), ash rock is a mineral material not found in nature. It is characterized by a high alkaline reaction,

excessive calcium and sodium content, and the absence of plant-available phosphorus and nitrogen. Therefore, treatments to improve these properties are necessary during biological remediation. Consequently, a comprehensive evaluation of the feasibility of utilizing power plant ash as a substrate for seedlings is imperative to ensure environmental sustainability and plant health.

This study presents an innovative approach to the evaluation of thermal power plant waste, which has gained increasing importance in recent years in terms of environmental sustainability and waste management. While fly ash generated from thermal power plants is typically regarded as an environmental threat, this research experimentally investigates the potential use of such waste materials in seedling cultivation substrates. This application, which has limited examples in the existing literature, contributes both to the reutilization of industrial waste and the development of alternative, low-cost, and environmentally friendly growing media for seedling production. In this respect, the study holds multidisciplinary innovation potential in the fields of environmental management and sustainable forestry-agricultural practices.

The present study aimed to evaluate the effects of different concentrations of thermal power plant ash (TPPA) on the germination percentage (GP), mean germination time (MGT), seedling growth parameters, and biomass allocation of containerized 1+0 stone pine (*Pinus pinea*) seedlings. The experiment compared the impact of TPPA incorporation with that of conventional nursery media to determine its potential as an inorganic soil amendment. By assessing seedling performance across varying TPPA levels, this study sought to explore its feasibility in enhancing soil properties and supporting sustainable nursery practices.

2. Materials and methods

2. 1. Seed material, preparation of media and sowing of stone pine seeds

Stone pine cones were collected from 20 mature trees growing in natural populations in Bergama, Izmir, Türkiye. After collection, the cones were carefully dried to facilitate seed extraction. The extracted seeds were then subjected to a floating test in water to separate viable (sound) seeds from empty or non-viable ones. Only the sound seeds, which sank during the test, were selected for use in the experiment. These seeds were subsequently placed in plastic bags to prevent moisture loss and stored in a refrigerator at a controlled temperature of +3°C ±1°C until the sowing period in the forest nursery.

The research was conducted at Istanbul University-Cerrahpaşa, Faculty of Forestry, located in Bahçeköy, Sarıyer, Istanbul-Türkiye, at an altitude of 126 m asl. The study site experiences a humid, mesothermal, and maritime climate, characterized by a moderate water deficit during the summer months, according to Thornthwaite's classification. The region receives an average annual precipitation of approximately 1,096 mm, while the mean annual temperature is 13.2°C (Baylan and Ustaoğlu, 2020).

For the experiment, plastic containers measuring 18 cm in height and 190 cm^3 in volume were used for sowing stone pine seeds. The study was designed as a randomized block experiment with four replications, incorporating six different growing media per replication to evaluate the effects of thermal power plant ash (TPPA) on seed germination and seedling development, with a total of 30 seedlings obtained per treatment.

The TPPA used in the study was sourced from the Biga Thermal Power Plant in Çanakkale, Türkiye. The İÇDAŞ Biga thermal power plant has an installed capacity of 405 MWe and utilizes fluidized bed combustion technology, a type of clean coal combustion technology. The plant uses coal as the main fuel and natural gas as an auxiliary fuel. Coal is conveyed from the stockyard to the boiler via a closed conveyor belt system and burned in the fluidized bed boiler with the addition of limestone. The gases released as a result of combustion in the boiler are passed through electrostatic dust collector filters, thus removing dust, before being directed to the chimney. The chemical composition of thermal power plant ash (TPPA) consists predominantly of silica (SiO_2) at 55.130%, followed by alumina (Al_2O_3) at 17.000% and iron oxide (Fe_2O_3) at 10.180%. Calcium oxide (CaO) is present at 9.800%, while the remaining components occur in smaller amounts, including magnesium oxide (MgO) at 1.690%, potassium oxide (K_2O):1.730%, and sulfur trioxide (SO_3): 2.170%. Minor constituents include sodium oxide (Na_2O): 0.911%, titanium dioxide (TiO_2): 0.580%, and manganese oxide (MnO): 0.128%, making the ash overall silica-rich with significant alumina and iron oxide content, along with moderate calcium oxide and trace amounts of other oxides (İÇDAŞ, 2019). The experimental media were prepared by mixing TPPA with sand in different proportions by volume, as follows:

- 100% conventional nursery media (control)

- 100% sand (control)
- 5% TPPA + 95% sand
- 15% TPPA + 85% sand
- 30% TPPA + 70% sand
- 100% TPPA

The conventional nursery media, commonly used in seedling production, consisted of two parts soil, one-part peat, and one-part river sand. The 100% sand media was also included as a control to compare the effects of TPPA application. The physical and chemical properties of all media were analyzed, and the results are presented in Table 1.

At the end of February, sound stone pine seeds were sown in the plastic containers, and germination progress was monitored two to three times per week for a period of 120 days. The germination percentage (GP) was calculated as the ratio of germinated seeds to the total number of sown seeds. The mean germination time (MGT) was determined using the formula (Bewley and Black, 1994); $MGT = \sum (t \times n)/\sum n$ where: t represents the number of days since the start of the germination test, n represents the number of seeds that germinated on day t.

2.2 Elemental analysis of samples

The concentration of $CaCO_3$ in soil samples was determined using a Scheibler calcimeter. Soil pH and EC measurements was performed in soil-water suspensions (1/2,5-w/v and 1/5 w/v, respectively) with pH-meter (Hanna Instruments Inc., Woonsocket-USA) and EC-meter (WTW, Xylem Analytics, Weilheim-Germany). The Bouyoucos hydrometer procedure was followed for sand, silt and clay contents. LECO Truspec CN-2000 analyzer (Leco Corp., St Joseph, Miami-USA) was employed for the determination of total carbon and nitrogen concentrations as dry combustion.

2.3 Biomass samplings

To evaluate the effects of thermal power plant ash (TPPA) on seedling growth and biomass allocation, twelve 1-year-old stone pine seedlings were harvested from each growing media. Each seedling was carefully separated into its main components, including needles, stems, and roots (main root and lateral roots). To determine dry biomass, subsamples of these components were oven-dried at 70°C until a constant weight. Several morphological parameters were measured, including seedling height, root length, root collar diameter, number of lateral branches, total needle weight, stem weight, main root weight, and lateral root weight. The total dry weight of each seedling was calculated by summing the dry weights of its components. Additionally, the proportion of each component's dry weight relative to the total seedling biomass was determined. After subsamples were ground, total carbon and nitrogen concentrations were analyzed with LECO Truspec CN-2000 analyzer (Leco Corp., St Joseph, Miami-USA).

2.4 Statistical analysis

The mean values and standard errors were used to represent the measured seedling traits, ensuring accurate depiction of variations among treatments. To determine statistical differences between the different growing media, a one-way analysis of variance (ANOVA) was performed. For post-hoc comparisons, Duncan's multiple range test was applied to identify significant differences between treatment means. A *p-value* of less than 0.05 ($p < 0.05$) was considered statistically significant. All statistical analyses were conducted using SPSS software (IBM® SPSS® Statistics International Business Machines Corporation (IBM), Armonk, New York, USA).

3. Results

The results indicated that there were no statistically significant differences in germination percentage (GP) and mean germination time (MGT) among the different growing media with varying thermal power plant ash (TPPA) ratios ($p > 0.05$, Table 2). Under the different media conditions, stone pine seeds germinated at rates ranging from 54% to 81%. The highest GP (81%) was observed in the 100% sand and 5% TPPA + 95% sand media, while the lowest GP (54%) occurred in the 100% TPPA media. Interestingly, seed germination in the 5% TPPA + 95% sand media was slightly higher than in the 100% conventional nursery media, suggesting that a low TPPA concentration did not negatively affect germination. However, as TPPA content increased beyond 5%, a gradual decline in GP was observed, with a notable decrease beginning at 15% TPPA + 85% sand. Regarding MGT, the shortest germination period (58 days) was recorded in the 100% conventional nursery media (Table 2, Figure 1).

Most of the seedling traits of stone pine seedlings showed statistically significant differences among the different growing media, except for stem biomass, needle biomass/total seedling biomass, above-ground biomass/total seedling biomass, and root biomass/total seedling biomass ($p < 0.05$, Table 3). The tallest seedlings and those with the longest root systems were observed in the 5% TPPA + 95% sand media, followed by seedlings grown in the 100% conventional nursery media. Similarly, root collar diameter was highest in the 100% conventional media, with the 5% TPPA + 95% sand media ranking second.

In contrast, seedlings grown in the 15% TPPA + 85% sand media exhibited the highest values for needle biomass, root biomass, above-ground biomass, total seedling biomass, and root biomass/stem biomass ratio, suggesting that a moderate TPPA addition may enhance below-ground growth. However, as TPPA concentration increased beyond 15%, a significant decline in all seedling traits was observed, except for the stem biomass/total seedling biomass ratio (Table 3).

The concentrations of nitrogen (N), carbon (C), and the C/N ratio in the needles, stems, and roots of stone pine seedlings under different thermal power plant ash (TPPA) treatments are presented in Table 4. Among these parameters, statistically significant differences were observed only in needle and root nitrogen content (N%) and the C/N ratio of needles ($p < 0.05$). The highest nitrogen content (N%) in needles was recorded in seedlings grown in 30% TPPA + 70% sand media, followed by those in the 100% TPPA media. In contrast, the highest root nitrogen content (N%) was found in seedlings grown in the 100% conventional nursery media.

4. Discussion

The findings of present study suggest that thermal TPPA can be used as a growing media amendment for stone pine seedlings, albeit with certain limitations. GP and MGT did not exhibit statistically significant differences across the different media compositions, indicating that TPPA does not directly inhibit seed germination. However, the highest GP was recorded in the 5% TPPA + 95% sand media, while increasing TPPA content beyond this level led to a decline in GP. This suggests that a low concentration of TPPA may provide some beneficial effects, possibly due to the presence of essential nutrients, while higher concentrations may negatively affect germination due to factors such as increased salinity or altered pH levels.

Yu et al. (2019) stated that overall, ash application reduced total biomass production by approximately 15%. However, in low-rate applications (<25% of soil mass), biomass increased by 11.6–29.2%, whereas in high-concentration applications (50–100%), biomass decreased by 45.8%. Additionally, although ash application led to an increase in aboveground biomass yield, belowground biomass showed a decreasing trend.

In a study on *Terminalia arjuna*, Ramesh et al. (2024) examined germination behavior, physiological response, and early seedling growth performance. Five different growing media were prepared with varying concentrations of fly ash and soil: control, 20% fly ash + soil, 40% fly ash + soil, 60% fly ash + soil, 80% fly ash + soil, and 100% fly ash. Thirty days after sowing, the highest germination rate (60%), survival rate (91%), plant height, root collar diameter, root length, and seedling quality index were observed in the media containing 20% fly ash.

Seedling growth parameters, including height, root length, and root collar diameter, were also significantly influenced by the growing media. The best results were obtained in conventional nursery media and in 5% TPPA + 95% sand, suggesting that TPPA in small amounts can support seedling development. Conversely, a significant decline in growth traits was observed with increasing TPPA content, particularly in 30% TPPA + 70% sand and 100% TPPA media. This decline could be attributed to the higher electrical conductivity (EC) values and possible toxicity effects at elevated TPPA concentrations. The decline in seedling performance at higher TPPA levels has been linked to the physicochemical properties of the growing media. Higher TPPA concentrations increase electrical conductivity (EC) and pH. High EC can reduce water uptake by causing osmotic stress, while high pH can limit the availability of essential nutrients such as phosphorus and micronutrients. These factors likely contributed to the reduced germination and growth observed at higher TPPA levels.

Thermal power plant ash contains essential plant nutrients such as calcium (Ca), potassium (K), and magnesium (Mg). At low application rates (e.g., 5% TPPA), these elements can improve seedling development by enhancing key physiological processes. Calcium plays a role in cell wall formation and root development, potassium regulates osmotic balance and enzyme activity, and magnesium is a central component of chlorophyll and is involved in photosynthesis. At low concentrations, these nutrients can support plant growth without causing adverse effects related to salinity or alkalinity.

Yu et al. (2019) stated that while thermal power plant ash contains various toxic elements, it also has nutrient content and can be used as a soil amendment due to its biomass growth-promoting properties and this decline could be attributed to the higher electrical conductivity (EC) values and possible toxicity effects at elevated TPPA concentrations.

Ansari et al. (2024) investigated the effect of different concentrations of fly ash on the growth, biochemical parameters and essential oil constituents of *M. arvensis*. The findings demonstrated that fly ash improved some important physical and chemical properties of soil. Specifically, the incorporation of fly ash-amended soil (10%) into the growth medium resulted in significant enhancements in various physiological parameters, including photosynthetic pigments, protein, proline, antioxidant activity, and mineral contents. Conversely, higher fly ash doses (25%) were found to induce oxidative stress, as evidenced by increased lipid peroxidation and electrolytic leakage levels, which exerted a detrimental effect on all parameters.

Yılmaz (2015) investigated whether the ash generated from lignite coal combustion, which is used in significant amounts for industrial and heating purposes, could be utilized as a soil conditioner in agricultural soils. The study aimed to determine the applicable doses if the ash was found to be suitable for use. The experimental results indicated that incorporating coal ash into the soil at rates of 5% or lower enriched the soil with essential plant nutrients, including nitrogen, organic matter, plant-available potassium, copper, manganese, iron, calcium, zinc, and magnesium. The best results for vetch growth were observed at a 5% ash application rate. Additionally, while the ash increased the pH of acidic soils, it did not cause any adverse effects on soils with higher pH levels.

Biomass allocation results further support these findings, as seedlings grown in the 5% TPPA media exhibited relatively balanced biomass distribution across roots, stems, and needles. The highest root biomass values were obtained in 15% TPPA + 85% sand, which could indicate an adaptive response to lower nutrient availability in higher ash-content media.

However, total seedling biomass significantly declined in 100% TPPA, reinforcing the adverse effects of excessive TPPA incorporation.

Elemental analysis of seedling tissues revealed notable differences in nitrogen and carbon concentrations across the treatments. The highest needle N% was observed in 30% TPPA + 70% sand, which may indicate increased nitrogen uptake in this treatment. However, root N% was highest in the conventional media, suggesting that excessive TPPA may disrupt root nutrient uptake efficiency. The increase in needle nitrogen concentration at higher TPPA levels, despite reduced overall growth, may be explained by a concentration effect resulting from reduced biomass accumulation. In other words, when growth is inhibited (as observed in higher TPPA treatments), nutrients such as nitrogen may accumulate in plant tissues due to limited dilution through biomass production. Nitrogen is a highly variable nutrient in cycle; its uptake, use, and transfer to plants undergo many changes. Nitrogen nutrition values in plants have also been obtained in nitrogen-poor ecosystems such as sand dunes and mining areas (Karatepe et al., 2020; Makineci 2021; Pehlivan et al., 2026). Although our study is short-term and a nursery experiment, some studies on plant cultivation in thermal power plant ash have yielded various results. For example, Gilewska et al., (2020) analyzed selected physical and chemical parameters of an unrecovered part of the waste site created for the disused Poland-Adamów power plant in terms of their potential to support vegetation growth and development. The reaction is alkaline (pH 9.68-12.19 in 1 M KCl). The organic matter in the rock was identified as unburned coal residues. Their analyses showed that it contained no nitrogen (0.06-0.31 g/kg) and phosphorus (1.8-14.1 g/kg), but excessive amounts of Ca and Na. Similarly, Kaczmarek et al., (2021) reports that in fly ash disposal sites (dry landfill) of the Adamów lignite power plant where afforestation was carried out, in addition to particle size and soil water relationships, low organic matter (51.5-86.3 g/kg) and nitrogen (1.11-2.43 g/kg) values are observed with $CaCO_3$: 5.7-9.5%, and pH.H_2O:7.9-8.5. Results may include species-specific differences; for example, in Poland, black locust, ash-leaf maple, common maple, and American ash species were planted in power plant ash, seawage sludge, and clay areas at the same thermal power plant site. The best survival was determined in black locust, and the worst in ash-leaf maple (Szadek et al., 2023).

In addition to these comments, Ots et al., (2017) reported that, in a study highly similar to ours, biofuel ashes significantly influenced both biomass growth and nutrient uptake in birch (*Betula pendula* Roth) and Scots pine (*Pinus sylvestris* L.) seedlings planted in harvested peatland areas. The best results were obtained with mixed ash applications on birch seedlings. In these areas, the height growth of birch seedlings was 2–3 times greater in the first year, 5–7 times greater in the second year, and 8–9 times greater in the third year. In contrast, the height growth of Scots pine seedlings in mixed ash applications was relatively weaker. The use of oil shale had the lowest effect on height growth. When compared to the control plots, the annual height increments of Scots pine seedlings in the mixed ash application were 1.4 times greater in the first year, 3 times greater in the second year, and 5 times greater in the third year.

Singh et al. (1997) reported that moderate mixtures of fly ash from thermal power plants positively influenced seed germination and seedling growth in *Vicia faba*, whereas high-dose applications significantly inhibited both germination and seedling development. In their experiment, similar to our study, fly ash was mixed with sandy loam soil at rates of 5%, 10%, 20%, and 30%, and healthy *Vicia faba* seeds were sown in these mixtures for open-air germination. Observations were made at two-day intervals. While seed germination increased by 6–8% in low-ash treatments, the 30% ash application reduced germination by 35%. In the 20% ash treatment, no reduction in germination percentage was observed; however, germination was delayed by four days.

Dwibedi et al. (2023) suggests that, considering both economic feasibility and environmental impacts, a soil mixture comprising 40% soil, 20% fly ash, and 40% vermicompost may be recommended for farmers for raising wet rice nurseries, as well as for remediating coal fly ash within agricultural production systems. A study was conducted by Agaç et al. (2024) with the objective of ascertaining the impact of varying levels of fly ash on wheat (*Triticum aestivum*) plants, and to determine the optimal applications of fly ash. The findings revealed that low applications of fly ash (1500, 3000 and 6000 ppm) enhanced the emergence rate and critical growth parameters, including plant height and dry weight, of wheat plants. Conversely, higher applications of fly ash (12,000 ppm) exhibited a deleterious effect, characterized by a decline in seedling height, wet weight, and leaf area of wheat.

5. Conclusions

The study suggests that thermal power plant ash (TPPA) can be used as a growing media amendment for stone pine seedlings, with some limitations. The highest GP occurred in the 5% TPPA + 95% sand media, but higher TPPA levels reduced GP. Seedling growth parameters were significantly affected by the media. The best results were in conventional nursery media and 5% TPPA + 95% sand, indicating low TPPA levels support growth. Biomass allocation results confirm these findings, with 5% TPPA seedlings showing balanced growth. However, total biomass declined in 100% TPPA, highlighting its negative effects. Needle N% was highest in 30% TPPA and 100% TPPA, indicating increased uptake, while root N% peaked in conventional media, suggesting excessive TPPA may hinder root nutrient absorption. Overall, these results align with previous studies highlighting the potential use of coal combustion residues as soil amendments, provided that their application rates are carefully managed to mitigate potential adverse effects.

The present study demonstrated that incorporating small amounts of TPPA into nursery growing media can influence the germination and growth of stone pine seedlings. A TPPA proportion of 5% in sand-based media was found to be the most effective for promoting seedling establishment without causing negative physiological effects. However, increasing TPPA content beyond this threshold led to diminished growth performance and reduced biomass accumulation, likely due to changes in soil chemical properties such as pH and electrical conductivity. Based on these findings, TPPA could be considered a potential amendment for sustainable nursery production, particularly as a means of recycling industrial waste. However, further research is necessary to assess its long-term effects on soil health and plant development in field conditions.

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The authors declare no conflict of interest for this publication.

References

Agaç, H., Erdoğan, G., & Yalçın, F.S., 2024, Farklı uygulama seviyelerindeki termik santral uçucu külünün buğday (*Triticum aestivum* L.) bitki gelişimi parametreleri üzerine etkisi. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi 7(1), 276-293, [in Turkish]. https://doi.org/10.47495/okufbed.1294400

Akgül, Ç., & Yoncacı, S., 2021, Türkiye kömür yakıtlı termik santral uçucu külleri. ISBN: 978-975-8136-33-9, Türkiye Çimento Sanayicileri Birliği Derneği, Ankara, [in Turkish].

Andrae, A.S., 2020, Hypotheses for primary energy use, electricity use and CO_2 emissions of global computing and its shares of the total between 2020 and 2030. Transactions on Power Systems 15, 50-59. https://doi.org/10.37394/232016.2020.15.6.

Ansari, M.S., Ahmad, G., Khan, A.A., & Mohamed, H.I., 2024, Evaluation of coal fly ash for reinforcing the plant growth, antioxidant properties, and essential oil content of *Mentha arvensis* L.: A Sustainable Approach to Coal Waste Management. Journal of Soil Science and Plant Nutrition 24(1), 1369-1393. https://doi.org/10.1007/s42729-024-01642-y

Baylan, K.A., & Ustaoğlu, B., 2020, Emberger biyoiklim sınıflandırmasına göre Türkiye'de Akdeniz biyoiklim katlarının ve alt tiplerinin dağılışı. Ulusal Çevre Bilimleri Araştırma Dergisi 3(3), 158-174, [in Turkish].

Bewley, J.D., & Black, M., 1994, Seeds: Physiology of development and germination. Plenum, New York.

Boydak, M., & Çalışkan, S., 2015, Afforestation in arid and semi-arid regions. The General Directorate of Combating Desertification and Erosion, Ankara.

Boydak, M., & Çalışkan, S., 2021, Ağaçlandırma, [Afforestation]. Second edition. Ogem-Vak, Istanbul, [in Turkish].

Çalışkan, S., & Boydak, M., 2017, Afforestation of arid and semiarid ecosystems in Turkey. Turkish Journal of Agriculture and Forestry 41(5), 317-330. http://dx.doi.org/10.3906/tar-1702-39.

Delić, D., Stajković-Srbinović, O., & Buntić, A., 2022, Hazards and usability of coal fly ash, in: Saljnikov, E., Mueller, L., Lavrishchev, A., Eulenstein, F. (Eds.), Advances in Understanding Soil Degradation. Innovations in Landscape Research. Springer, Cham. pp. 571-608.

Dwibedi, S. K., Sahu, S. K., Pandey, V. C., Rout, K. K., & Behera, M., 2023, Seedling growth and physicochemical transformations of rice nursery soil under varying levels of coal fly ash and vermicompost amendment. Environmental Geochemistry and Health 45(2), 319-332. https://doi.org/10.1007/s10653-021-01074-y

Enerjigunlugu, 2023, Türkiye 2023'te elektriğinin üçte birinden fazlasını kömürden üretti. Retrieved May 6, 2025, from https://www.enerjigunlugu.net/turkiye-2023te-elektriginin-ucte-birinden-fazlasini-komurden-uretti-57432h.htm. [in Turkish].

Evaristo, I., Batista, D., Correia, I., Correia, P., & Costa, R., 2010, Chemical profiling of Portuguese *Pinus pinea* nuts. Journal of the Science of Food and Agriculture 90, 1041–1049. https://doi.org/10.1002/jsfa.3914.

Gajić, G., Djurdjević, L., Kostić, O., Jarić, S., Mitrović, M., & Pavlović, P., 2018, Ecological potential of plants for phytoremediation and ecorestoration of fly ash deposits and mine wastes. Frontiers in Environmental Science 6, 124. https://doi.org/10.3389/fenvs.2018.00124.

Gilewska, M., Otremba, K., & Kozlowski, M., 2020, Physical and chemical properties of ash from thermal power station combusting lignite. A case study from central Poland. Journal of Elementology 25(1), 279-295. DOI: 10.5601/jelem.2019.24.4.1886.

İÇDAŞ, 2019. Kalite kontrol kimyasal analiz raporu, (9.07.2019), form no: KKKF-17, revize tarih no:02,05,2014/0. Biga-Çanakkale, Türkiye. [in Turkish].

Kaczmarek, Z., Mocek-Płóciniak, A., Gajewski, P., Mendyk, Ł., & Bocianowski, J., 2021, Physical and soil water properties of technosols developed from lignite fly ash. Archives of Environmental Protection 47(2), 95-102. DOI: 10.24425/aep.2021.137281.

Karatepe, Y., Külcüoğlu, C., & Makineci, E., 2020, Comparison of soil properties of an adjacent clay mine spoil, a mining site reclaimed with stone pine (*Pinus pinea* L.) plantation and a natural forest. Applied Ecology & Environmental Research 18(5), 6857-6874. DOI: http://dx.doi.org/10.15666/aeer/1805_68576874.

Makineci, E., 2021. Nitrogen accumulation in forest floors with introduced *Pinus pinea* and *Pinus pinaster* in dune site. Environmental Monitoring and Assessment 193(6), 327. https://doi.org/10.1007/s10661-021-09100-3.

Mathapati, M., Amate, K., Prasad, C.D., Jayavardhana, M.L., & Raju, T.H., 2022, A review on fly ash utilization. Materials Today 50, 1535-1540. https://doi.org/10.1016/j.matpr.2021.09.106.

Mutke, S., Calama, R., González-Martínez, S.C., Montero, G., Javier, Gordo, F., Bono, D., & Gil, L., 2012, Mediterranean stone pine: botany and horticulture. Janick, J. (Eds.), Horticultural Reviews. Wiley-Blackwell pp. 153–201.

Ots, K., Tilk, M., & Aguraijuja, K., 2017, The effect of oil shale ash and mixtures of wood ash and oil shale ash on the above-and belowground biomass formation of Silver birch and Scots pine seedlings on a cutaway peatland. Ecological Engineering 108, 296-306. https://doi.org/10.1016/j.ecoleng.2017.09.002

Panda, D., Mandal, L., & Barik, J., 2020, Phytoremediation potential of naturally growing weed plants grown on fly ash-amended soil for restoration of fly ash deposit. International Journal of Phytoremediation 22(11), 1195-1203. https://doi.org/10.1080/15226514.2020.1754757.

Pehlivan, S., Makineci, E., Özturna, A. G., & Tolunay, D., 2026, Biomass, carbon, and nitrogen relations between tree foliage and organic soil layers with stand development of *Pinus pinaster* over dune restoration. Land Degradation & Development, 2026, 0:1-15. https://doi.org/10.1002/ldr.70507

Ramesh, S., Patil, G., & Jaiswal, M., 2024, Studies on Germination behaviour and Physiological response of *Terminalia arjuna* (Roxd.) towards fly-ash during its initial stage Ecology Environment and Conservation 30(1), 78-83. https://doi.org/10.53550/eec.2024.v30i01.014.

Singh, S.N., Kulshreshtha, K., & Ahmad, K.J., 1997, Impact of fly ash soil amendment on seed germination, seedling growth and metal composition of *Vicia faba* L. Ecological Engineering 9, 203–208. https://doi.org/10.1016/S0925-8574(97)10004-0.

Szadek, P., Pająk, M., Michalec, K., Wąsik, R., Otremba, K., Kozłowski, M., & Pietrzykowski, M., 2023, The impact of the method of reclamation of the coal ash dump from the “Adamów” Power Plant on the survival, viability, and wood quality of the introduced tree species. Forests 14(4), 848. DOI: 10.3390/f14040848.

Yılmaz, S., 2015, Kömür külünün toprakların kimyasal özelliklerine ve bitki gelişimine etkisi. Yüksek Lisans Tezi (Master of Science), Namık Kemal Üniversitesi-Tekirdağ, Türkiye. [in Turkish].

Yu, C.L., Deng, Q., Jian, S., Li, J., Dzantor, E.K., & Hui, D., 2019, Effects of fly ash application on plant biomass and element accumulations: a meta-analysis. Environmental Pollution 250, 137-142. https://doi.org/10.1016/j.envpol.2019.04.013

Zhai, J., Burke, I.T., & Stewart, D.I., 2021, Beneficial management of biomass combustion ashes. Renewable and Sustainable Energy Reviews 151, 111555. https://doi.org/10.1016/ j.rser.2021.111555

Table 1. Chemical composition of thermal power plant ash (TPPA) added medias

	100% conventional media	100% sand	5% ash + 95% sand	15% ash + 85% sand	30% ash + 70% sand	100% ash	*p*-value
N (%)	0.17(0.01) c	0.06(0.01) b	0.03(0.01) ab	0.01(0.002) a	0.02(0.01) a	0.32(0.02) d	0.000
C (%)	5.16(0.20) d	1.53(0.04) a	1.66(0.04) a	2.49(0.06) b	3.77(0.09) c	11.11(0.06) e	0.000
C/N	30.88(0.58) cd	32.17(4.26) d	81.04(17.05) b	1123.89(303.59) a	560.13(109.93) a	35.65(1.67) c	0.000
Sand (%)	68.29(0.46) b	97.44(0.70) d	96.95(0.16) d	92.86(1.20) c	91.24(0.20) c	56.12(0.36) a	0.000
Silt (%)	13.98(0.57) c	1.27(0.73) a	2.24(0.22) a	6.20(1.14) b	7.53(0.26) b	40.24(0.54) d	0.000
Clay (%)	17.73(0.86) c	1.29(0.12) a	0.81(0.09) a	0.95(0.26) a	1.23(0.17) a	3.64(0.42) b	0.000
pH	7.47(0.05) a	8.03(0.03) bc	8.21(0.01) d	7.93(0.07) b	8.13(0.01) cd	8.15(0.05) cd	0.000
EC (µS/cm)	173.04(5.55) c	88.63(1.57) a	106.14(2.35) a	130.92(2.72) b	593.10(10.39) d	1265.60(13.21) e	0.000
$CaCO_3$ (%)	0,05 (0,01) a	7,61(0,06) e	5,46(0,02) d	4,09(0,08) c	3,78(0,02) b	5,62(0,11) d	0,000

Values are the mean, numbers in parenthesis are standard error, and values in the same row followed by the same letter are not statistically different at the 0.05 significance level in the Duncan post hoc test. N: total nitrogen, C: total carbon, EC: electrical conductivity

Table 2. Germination percentages (GP) and mean germination times (MGT) of the stone pine (*Pinus pinea*) seeds in the various media with the different rates of thermal power plant ash (TPPA)

	100% conventional media	100% sand	5% ash + 95% sand	15% ash + 85% sand	30% ash + 70% sand	100% ash	*p-value*
GP	76 (13) a	81 (7) a	81 (9) a	60 (5) a	59 (13) a	54 (12) a	0.239
MGT	58 (5) a	63 (7) a	60 (3) a	60 (1) a	71 (7) a	67 (6) a	0.480

Values are the mean, numbers in parenthesis are standard error, and values in the same row followed by the same letter are not statistically different at the 0.05 significance level in the Duncan post hoc test.

Table 3. Influence of thermal power plant ash (TPPA) added media on the stone pine (*Pinus pinea*) seedling traits.

	100% conventional media	100% sand	5% ash + 95% sand	15% ash + 85% sand	30% ash + 70% sand	100% ash	*p-value*
Seedling Height (mm)	26.393 (0.76) b	24.87 (0.61) ab	26.56 (0.90) b	25.98 (0.68) ab	24.13 (0.69) a	23.86 (0.77) a	0.036
Root Length (mm)	14.84 (0.60) ab	14.42 (0.37) ab	16.38 (0.73) a	14.78 (0.60) ab	13.99 (0.52) b	13.84 (0.56) b	0.032
Root Collar Diameter (mm)	2.15 (0.06) d	1.93 (0.08) bc	2.00 (0.05) cd	1.89 (0.06) abc	1.80 (0.05) ab	1.72 (0.04) a	0.001
Needle Biomass (g)	0.17 (0.01) b	0.17 (0.02) b	0.17 (0.02) b	0.21 (0.01) b	0.18 (0.01) b	0.12 (0.18) a	0.008
Stem Biomass (g)	0.07 (0.01) a	0.06 (0.004) a	0.07 (0.004) a	0.07 (0.01) a	0.07 (0.01) a	0.06 (0.01) a	0.124
Root Biomass (g)	0.05 (0.004) ab	0.06 (0.01) abc	0.07 (0.01) bc	0.08 (0.01) c	0.06 (0.01) abc	0.04 (0.01) a	0.026
Above-ground Biomass (g)	0.24 (0.02) b	0.23 (0.02) ab	0.25 (0.02) b	0.28 (0.02) b	0.25 (0.02) b	0.18 (0.03) a	0.024
Total Seedling Biomass (g)	0.29 (0.02) ab	0.29 (0.03) ab	0.31 (0.02) b	0.35 (0.03) b	0.31 (0.02) b	0.22 (0.03) a	0.022
Root Biomass / Stem Biomass	0.78 (0.07) a	0.99 (0.08) bc	0.92 (0.07) abc	1.05 (0.06) c	0.81 (0.04) ab	0.73 (0.07) a	0.005
Needle Biomass / Total Seedling Biomass	0.58 (0.01) ab	0.59 (0.01) b	0.55 (0.01) a	0.59 (0.01) b	0.57 (0.01) ab	0.55 (0.02) a	0.220
Stem Biomass/ Total Seedling Biomass	0.24 (0.01) bc	0.21 (0.01) ab	0.24 (0.01) bc	0.20 (0.01) a	0.24 (0.01) bc	0.27 (0.02) c	0.001
Above-ground Biomass / Total Seedling Biomass	0.82 (0.01) b	0.80 (0.01) ab	0.79 (0.01) a	0.79 (0.01) ab	0.81 (0.01) ab	0.82 (0.01) ab	0.097
Root Biomass / Total Seedling Biomass	0.18 (0.01) a	0.20 (0.01) ab	0.21 (0.01) b	0.21 (0.01) ab	0.19 (0.01) ab	0.18 (0.01) ab	0.096

Values are the mean. numbers in parenthesis are standard error. and values in the same row followed by the same letter are not statistically different at the 0.05 significance level in the Duncan post hoc test.

Table 4. Total carbon and nitrogen concentrations of stone pine (*Pinus pinea*) seedlings on thermal power plant ash (TPPA) added media.

		100% Conventional Media	100% Sand	5% Ash + 95% Sand	15% Ash + 85% Sand	30% Ash + 70% Sand	100% Ash	*p-value*
N%	Needle	1.31(0.06) ab	1.24(0.03) a	1.30(0.01) ab	1.31(0.02) ab	1.51(0.04) c	1.37(0.01) b	0.000
	Stem	1.07(0.12)	1.06(0.02)	1.20(0.04)	1.05(0.01)	1.20(0.01)	1.14(0.03)	0.192
	Root	0.95(0.06)	0.89(0.03)	0.82(0.04)	0.78(0.04)	0.84(0.02)	0.80(0.02)	0.034
C%	Needle	45.78(0.99)	46.93(0.63)	46.03(0.14)	46.34(0.35)	47.39(0.43)	46.40(0.57)	0.424
	Stem	45.97(1.51)	46.81(0.49)	46.15(0.54)	46.13(0.22)	47.23(0.48)	46.30(0.44)	0.820
	Root	42.95(0.75)	44.58(1.07)	41.89(0.49)	41.72(0.61)	42.59(1,19)	40.60(0.83)	0.062
C/N	Needle	35.15(1.15) b	37.93(0.98) c	35.48(0.33) b	35.54(0.71) b	31.42(0.70) a	33.85(0.57) b	0.000
	Stem	45.16(4.43)	44.12(0.71)	38.56(1.23)	44.05(0.41)	39.32(0.62)	40.97(1.55)	0.133
	Root	46.00(3.06)	49.97(0.97)	51.37(1.93)	53.81(1.75)	50.98(0.85)	50.98(0.99)	0.102

Values are the mean, numbers in parenthesis are standard error, and values in the same row followed by the same letter are not statistically different at the 0.05 significance level in the Duncan post hoc test.

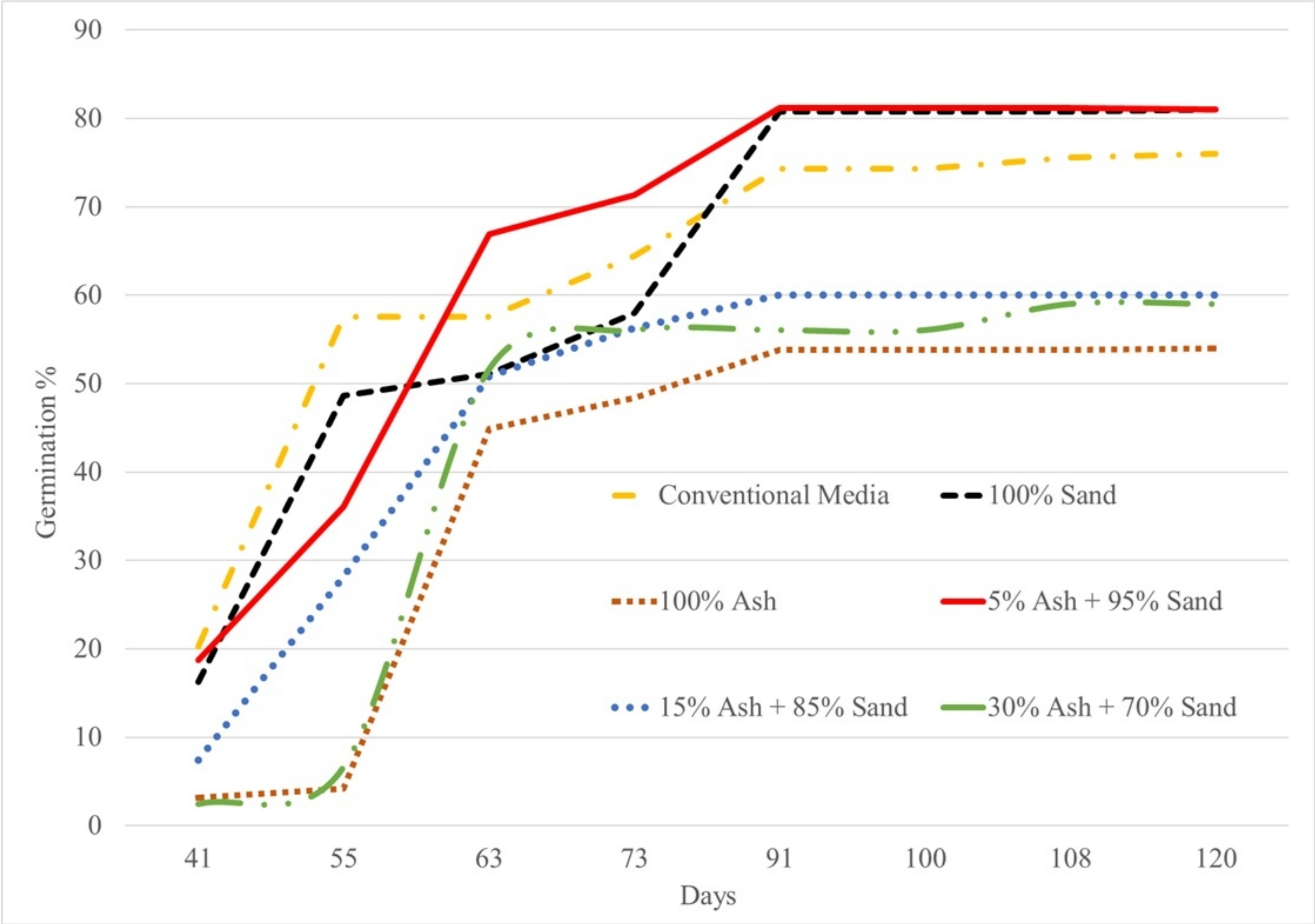

Figure. 1 Influence of thermal power plant ash (TPPA) added media on the germination of stone pine (*Pinus pinea*) seeds