Research Article

Microbial-Enhanced Boiler Ash as a Sustainable Soil Amendment

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Abstract | The increasing costs of ash disposal and the global drive for sustainable agriculture have created opportunities to repurpose wood-fired boiler ash as a soil amendment. Boiler ash is rich in essential macronutrients such as potassium, calcium, and phosphorus, and its alkaline properties suggest potential for soil pH correction. However, its direct use often provides inconsistent results due to limited nutrient bioavailability. In this study, the potential of boiler ash, both alone and in combination with *Bacillus* sp., was evaluated as a soil conditioner for *Brassica rapa* subsp. *chinensis* (pak choi). A controlled pot experiment was conducted with three treatments consisting of untreated soil (T0), soil with boiler ash (T1), and soil with boiler ash plus *Bacillus* sp. (T2). Amendments were incorporated into topsoil at a five percent application rate, and plants were grown for three weeks under standardized conditions of temperature, humidity, and watering in a completely randomized design. The results showed that boiler ash application increased soil alkalinity (pH 10.6) and supplied macronutrients such as potassium (19.28 meq/100g) and calcium (14.65 meq/100g), while the microbial-enhanced amendment further improved nitrogen availability. Plants in T2 exhibited significantly greater growth, producing approximately 33% more leaves, nearly threefold higher root biomass, and 80% longer roots compared to the control. These improvements were attributed to microbial contributions such as nutrient solubilization, phytohormone production, and enhanced root development. This study highlights the novelty of integrating *Bacillus* sp. with boiler ash to transform an industrial byproduct into a multifunctional soil conditioner that enhances nutrient dynamics and crop growth. The findings not only demonstrate a practical strategy for reducing dependence on synthetic fertilizers but also contribute to circular economy practices by converting waste into a valuable agricultural input.

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Introduction

Landfilling has long been the primary means of disposing of boiler ash from wood-based industries, but this practice is increasingly unsustainable due to rising disposal costs, limited landfill capacity, and associated environmental risks (Basu *et al.*, 2009). Boiler ash, a byproduct of biomass combustion, is rich in essential macronutrients such as calcium, potassium, magnesium, and phosphorus, and its alkaline nature makes it a potential substitute for agricultural lime. Recent work has shown that biomass combustion ash can improve soil pH, enhance nutrient solubilization, and increase crop yield when applied under controlled conditions (Baptista *et al*., 2023). Its high cation exchange capacity also suggests potential for nutrient retention and soil pH correction (Asquer *et al*., 2019). However, the direct application of ash poses challenges, as nutrient availability is often inconsistent, phosphorus is commonly present in insoluble forms, and repeated use may result in the accumulation of heavy metals and other toxic elements (Lopes and Proença, 2020; Hnydiuk-Stefan *et al*., 2024). These limitations restrict its agronomic effectiveness despite a promising nutrient profile.

Microbial biotechnology has emerged as a promising strategy to address such challenges by enhancing nutrient bioavailability and improving soil health (Tsotetsi *et al*., 2022). Plant growth-promoting rhizobacteria (PGPR), particularly members of the genus *Bacillus*, have received considerable attention for their role in sustainable agriculture. *Bacillus* spp. is well known for their ability to solubilize phosphorus and potassium, fix atmospheric nitrogen, and secrete phytohormones such as auxins, gibberellins, and cytokinins, which directly stimulate plant growth and development (Verma *et al*., 2024). These microbes also enhance soil structure, promote nutrient cycling, and help plants withstand abiotic stresses such as salinity, drought, and soil acidity (Jeguirim *et al*., 2017). Importantly, *Bacillus* spp. are spore-forming bacteria capable of surviving harsh environmental conditions, making them particularly well-suited for integration with inorganic soil amendments such as boiler ash.

The synergistic use of PGPR with mineral-rich byproducts like ash or biochar has been shown to improve nutrient release and soil microbial activity while enhancing crop productivity (Joseph *et al*., 2021; Baptista *et al*., 2023). For example, inoculation of phosphate-solubilizing bacteria in ash-based amendments has been reported to increase phosphorus availability through the secretion of organic acids and phosphatase enzymes (Timofeeva *et al*., 2023). Such interactions are particularly valuable for amendments like boiler ash, where much of the phosphorus exists in forms not readily accessible to plants. By mobilizing these nutrients and stimulating root development, PGPR can help unlock the agronomic potential of ash that would otherwise remain underutilized.

Although boiler ash and *Bacillus* spp. have been studied independently, their combined application as a soil conditioner remains poorly understood. Boiler ash represents an abundant yet underutilized industrial byproduct, while *Bacillus* spp. are proven plant growth promoters. However, the ways in which microbial inoculation modifies the chemical properties of ash, alters nutrient dynamics, and translates into crop yield improvements have not been adequately explored, particularly in vegetable production systems.

The problem addressed in this study is twofold. Agricultural systems face increasing pressure to reduce reliance on synthetic fertilizers, while wood-based industries struggle to manage growing volumes of boiler ash in an environmentally sustainable manner. Boiler ash provides an opportunity for nutrient recycling but suffers from inconsistent nutrient availability and potential environmental risks. Conversely, *Bacillus* spp. offers a biological mechanism for improving soil fertility but have rarely been tested in combination with ash-based conditioners. The research gap lies in the absence of studies investigating microbial-enhanced boiler ash as an integrated soil amendment for sustainable crop production.

The objective of this study was to evaluate the effects of boiler ash alone and in combination with *Bacillus* sp. on soil properties and the growth of *Brassica rapa* subsp. *chinensis* (pak choi). We hypothesized that the microbial-enhanced amendment would increase nutrient availability, improve plant growth, and provide greater agronomic benefits compared to ash applied alone.

Materials and Methods

Boiler ash collection

The boiler ash samples were collected from GP Plywood Sdn Bhd in Dungun, Terengganu, a plywood manufacturing facility that generates ash as an industrial byproduct from its wood-fired boiler operations as shown in Figure 1. The boiler ash, a residue derived from the combustion process used to power the factory, contained various unburned debris, including rocks, nails, iron fragments, and other incombustible materials. To ensure uniformity and safety for further analysis, the raw ash was sieved to remove coarse impurities, resulting in a finer, more homogeneous texture as shown in Figure 2. This sieving process facilitated safer handling and standardized the ashes for subsequent experimental applications.

Figure 1: *Boiler ash waste that were collected from the manufacturing facility*

Figure 2: *Sieved boiler ash used as raw material for soil amendment*

Figure 3: *Bacillus sp. cultivated in nutrient broth for soil amendment preparation.*

Microbial cultivation

A pure culture of *Bacillus* sp. was grown in nutrient broth (NB) prepared according to the manufacturer's instructions and sterilized by autoclaving at 121 °C for 20 minutes as illustrated in Figure 3. The culture was incubated at 30 °C for 24–48 hours to reach exponential growth before being used as inoculant. Culture purity was checked by streaking on agar plates and examining colony morphology. A fresh suspension was prepared for soil amendment, while long-term preservation was done as glycerol stock at –20 °C.

Figure 4: *Transplanted pak choi seedlings in polybags*

Soil and planting material

In Figure 4, one-week-old seedlings of *Brassica rapa* subsp. *chinensis* (pak choi) were purchased from a local nursery to ensure uniformity of growth stage. Polybags (30 × 35 cm) were filled with 4 kg of loamy topsoil that had been air-dried and sieved to remove plant residues. The soil had a neutral pH (6.8) and moderate organic matter content. Coconut fibre mulch was placed on top of each polybag to reduce moisture loss and suppress weed growth as shown in Figure 5.

Figure 5: *Pak choi seedlings with coconut fibre mulch*

Experimental treatments

Three treatments were established consisting of untreated control soil (T0), soil amended with 5% boiler ash by weight (T1), and soil amended with five percent boiler ash together with *Bacillus* sp. inoculant (T2). For T2, 50 mL of freshly prepared microbial suspension (10^8 CFU/ mL) was mixed into the soil-ash blend during preparation. All soil and amendment mixtures were prepared one week prior to transplanting to allow stabilization. The polybags were arranged in a completely randomized design with four replicates per treatment and maintained under controlled laboratory conditions at 28 ± 2°C with relative humidity of 60 ± 5% and a 14-hour light and 10-hour dark photoperiod. Watering was carried out daily to maintain approximately 70% field capacity. No additional fertilizers were applied during the experiment.

Plant growth measurement

Plant growth and development were monitored weekly for three weeks after transplanting. The number of leaves was determined by manually counting fully expanded leaves. At harvest, root length was measured by carefully uprooting the plants, washing the roots free of soil, and recording the length of the primary root with a ruler. Root biomass was obtained by oven-drying the roots at 65°C for 48 hours and weighing them to determine dry weight.

Statistical analysis

All data were analyzed using analysis of variance (ANOVA) in Minitab software (version 19). Treatment means were compared at a significant level of $p < 0.05$, and standard errors of the means were calculated. Replication number (n = 4) was chosen to balance statistical robustness with resource constraints, consistent with similar pot-based PGPR studies.

Results and Discussion

Wood-fired boiler ash properties

As shown in Table 1, the comparative analysis of wood-fired boiler ash (T1) and the soil conditioner (T2, boiler ash + *Bacillus* sp.) reveals significant differences in their chemical properties, highlighting the impact of microbial treatment on nutrient availability and soil amendment potential.

The boiler ash (T1) exhibited a high cation exchange capacity (CEC, 33.65 meq/100g), indicating strong nutrient retention, while the soil conditioner (T2) showed a reduced CEC (16.96 meq/100g), likely due to microbial modification of binding sites. Potassium (K) levels decreased slightly from 19.28 meq/100g in raw ash (T1) to 18.81 meq/100g in the conditioner (T2), possibly due to microbial uptake or transformation. Notably, calcium (Ca) content remained relatively stable at 14.65 meq/100g in ash (T1) versus 15.15 meq/100g in the conditioner (T2), suggesting microbial activity did not significantly alter this nutrient.

Table 1: *Physicochemical properties of boiler ash (T1) and soil conditioner (T2)*

	Boiler ash (T1)	Soil conditioner (T2)
pH	10.62	10.57
Total N (%)	0.07	0.10
Organic C (%)	5.11	6.40
P (mg/kg)	15.95	13.47
K (meq/100)	19.28	18.81
Mg (meq/100)	2.43	2.75
Ca (meq/100)	14.65	15.15
CEC (meq/100)	33.65	16.96

The decline in CEC and phosphorus in T2 compared with T1 suggests microbial transformation of ash-bound nutrients. *Bacillus* spp. is known to temporarily immobilize phosphorus during growth before releasing it in more soluble forms (Ichriani *et al.*, 2021). The observed increase in nitrogen and organic carbon in T2 is likely due to microbial biomass and metabolic activity. These changes indicate that microbial inoculation modifies ash chemistry in ways that can improve long-term nutrient availability compared to raw ash.

Growth parameter

The comparative analysis of plant growth parameters across the three treatments (T0, T1, and T2) over multiple transplant dates reveals important insights into the synergistic effects of microbial-enhanced soil amendments as illustrated in Figure 6. The control treatment (T0) showed baseline growth characteristics typical of unamended soil, serving as an important reference point for evaluating amendment efficacy (Jarosz-Krzemińska and Poluszyńska, 2020). The boiler ash treatment (T1) demonstrated moderate but consistent improvements in plant growth across all observation periods, with this enhancement becoming more evident at later stages of growth. This delayed response suggests that nutrient release from boiler ash amendments often follows a gradual trajectory as the material weathers and interacts with soil components (Abdelmoaty *et al*., 2022).

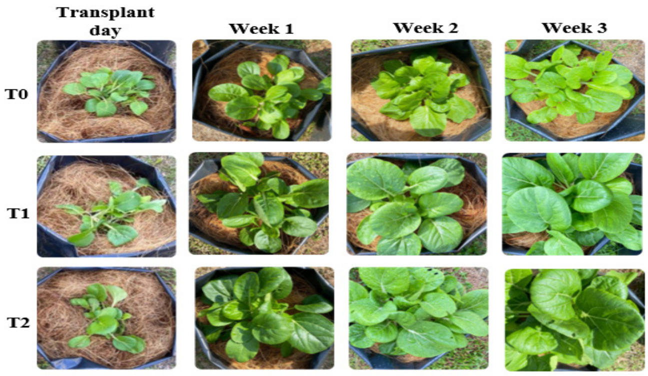

Figure 6: *Growth progression of Brassica rapa subsp. chinensis under three treatments: untreated control (T0), soil amended with boiler ash (T1), and soil amended with boiler ash + Bacillus sp. (T2). Images were taken at transplant day, Week 1, Week 2, and Week 3 after transplanting.*

Most significantly, the microbial-enhanced treatment (T2) exhibited superior growth performance throughout the experiment, with the magnitude of improvement becoming particularly pronounced at later transplant dates. This progression indicates that the beneficial effects of *Bacillus* sp. inoculation require time to become fully established in the soil-plant system. Research has demonstrated that *Bacillus* species improve plant growth through multiple mechanisms including solubilization of otherwise inaccessible nutrients, production of phytohormones such as auxins, gibberellins, and cytokinins, and the stimulation of systemic resistance which collectively enhance plant vigor ((Mohd Hanafi *et al*., 2018). Moreover, *Bacillus* sp. may enhance nutrient use efficiency by increasing the bioavailability of phosphorus, potassium, and nitrogen, while simultaneously regulating plant hormone balance to promote shoot and root development (Hossain, 2016).

The differential performance between T1 and T2 underscores a critical finding in soil amendment research. While boiler ash provides valuable mineral nutrients, its full agronomic potential often requires biological activation (Zainuddin *et al*., 2021). This is particularly true for phosphorus dynamics, where native phosphorus in boiler ash is largely insoluble and thus not readily available to plants. Phosphate-solubilizing bacteria such as *Bacillus* sp. convert these unavailable forms into soluble phosphorus through the release of organic acids and phosphatases, explaining the superior performance of the microbial-enhanced treatment (Wahyudin *et al*., 2020).

The improvement observed in T2 also suggests enhanced root development, as root length and mass increased substantially compared to T0 and T1. Enhanced root systems are crucial for efficient nutrient and water uptake, and several studies have reported that *Bacillus* sp. inoculation stimulates root elongation and branching, thereby expanding the rhizosphere and improving nutrient absorption (Wang & Wang, 2019; Mohammad *et al*., 2024). This biological advantage explains why microbial-enhanced treatments not only support better shoot growth but also strengthen belowground structures that sustain long-term productivity.

From a practical perspective, these results have important implications for sustainable agriculture and waste valorisation. They confirm that the simple application of industrial byproducts like boiler ash, while beneficial, represents an incomplete utilization strategy (Baptista *et al*., 2023). The integration of boiler ash with beneficial microbes can transform it from a basic soil conditioner into a multifunctional amendment that simultaneously improves nutrient availability, enhances hormone-mediated growth regulation, and strengthens root development. This approach aligns with circular economic principles by creating value from industrial waste while reducing dependence on conventional fertilizers (Bukit *et al*., 2022).

Table 2: *Effects of different soil treatments on leaf number, root mass, and root length*

Treatment	Number of leaves	Root biomass (g)	Root length (cm)
Control (T0)	6 ± 0.3 c	3 ± 0.2 c	5 ± 0.25 c
Boiler ash (T1)	7 ± 0.4 b	5 ± 0.3 b	6 ± 0.35 b
Soil conditioner (T2)	8 ± 0.5 a	9 ± 0.4 a	9 ± 0.45 a

Values are means ± standard error (n = 4). Means followed by different letters within the same column indicate significant differences at $p < 0.05$.

Growth and morphological

The measurements of leaf count, root biomass, and root length clearly demonstrate the differential effects of the three treatments on plant development as shown in Figure 7. Table 2 revealed that the control plants showed baseline growth characteristics with 6 leaves, 3 g root mass, and 5 cm root length, representing typical performance in unamended soil conditions. Application of boiler ash alone resulted in modest improvements across all parameters (7 leaves, 5g root mass, 6 cm root length), consistent with findings regarding the nutritional benefits of wood ash amendments (Tahir *et al*., 2022). However, the most significant enhancements were observed in the soil conditioner treatment, which produced plants with 8 leaves, 9 g root mass, and 9 cm root length where they represent increases of 33%, 200%, and 80% respectively over the control. This improvement was statistically significant, as indicated in Figure 8 and highlights the synergistic effect of combining boiler ash with *Bacillus* sp.

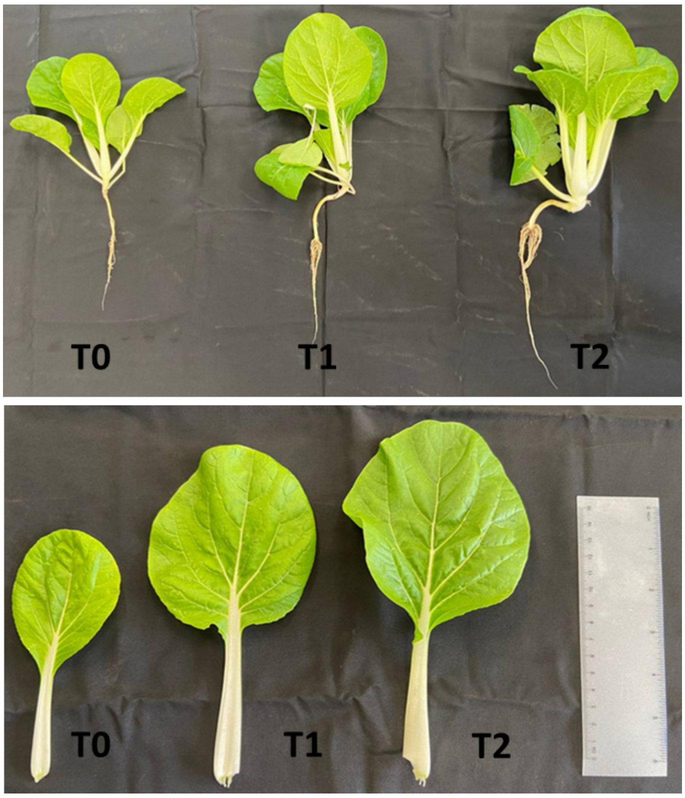

Figure 7: *Growth and leaf size variation in Brassica rapa (Pak Choi).*
(a) Whole plant morphology. (b) Representative leaves with size reference.

These results align strongly with recent research on plant growth-promoting rhizobacteria (PGPR). The particularly dramatic improvement in root development (mass and length) reveled *Bacillus* species' ability to produce auxins and other phytohormones that specifically stimulate root growth. The 200% increase in root mass is especially noteworthy that enhanced root systems directly correlate with improved nutrient and water uptake efficiency. The balanced improvement in both shoot (leaf count) and root parameters in the microbial-enhanced treatment contrasts with the more limited effects of boiler ash alone, underscoring the multifunctional benefits of biological activation of industrial byproducts (Joseph *et al*., 2021; Mathapati *et al*., 2022).

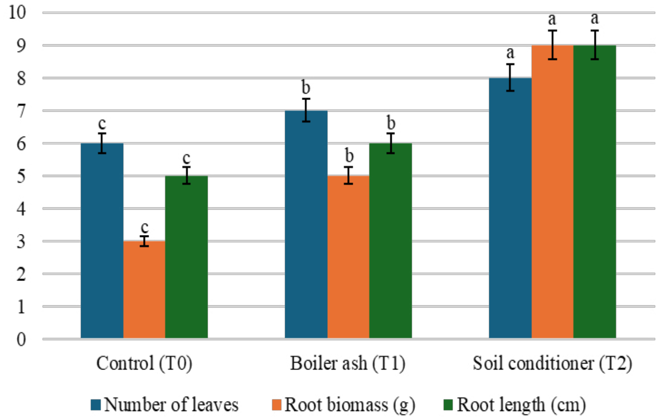

Figure 8: *Effects of different soil treatments on number of leaves, root biomass, and root length of pak choi. Values (n = 4) denoted by identical letters indicate no significant difference at $p < 0.05$. Error bars represent the standard errors of four replicates.*

Conclusions and Recommendations

This study demonstrated that wood-fired boiler ash possesses properties that make it suitable for use as a soil amendment, including high alkalinity, considerable potassium and calcium contents, and a high cation exchange capacity. However, when applied alone (T1), its effects on *Brassica rapa* subsp. *chinensis* growth were limited. In contrast, the integration of boiler ash with *Bacillus* sp. (T2) improved soil nutrient dynamics by increasing nitrogen availability and modifying cation exchange capacity, while also enhancing plant growth parameters such as leaf number, root biomass, and root length compared with both the untreated control (T0) and ash-only treatment (T1). These findings indicate that microbial-enhanced boiler ash has potential as a more effective soil conditioner than ash alone, supporting both crop performance and the valorization of industrial byproducts.

Despite these promising outcomes, several limitations must be acknowledged. The present study was conducted under controlled greenhouse conditions, with a short experimental duration and a single test crop. As such, the results cannot be directly generalized to field conditions or long-term soil management practices. In addition, while nutrient benefits were observed, the potential risks associated with repeated ash application such as heavy metal accumulation, were not assessed.

Future research should address these gaps by conducting multi-season field trials across different soil types and climatic conditions to validate the effectiveness of microbial-enhanced boiler ash under realistic farming systems. Optimization studies are also needed to determine ideal application rates for both ash and microbial inoculants that maximize benefits while safeguarding soil health. Research should extend to other crop species, focusing on yield and nutritional quality, and include assessments of soil microbial community dynamics. Long-term monitoring of potential environmental risks, especially metal accumulation, is essential to ensure safe agricultural use. Additionally, economic feasibility studies and cost–benefit analyses are required to evaluate the scalability of this approach, alongside collaborations with industries producing boiler ash to integrate such amendments into circular economy frameworks.

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Novelty Statement

This study provides new evidence that amending boiler ash with *Bacillus* sp. enhances its performance as a soil conditioner, leading to improved nutrient dynamics and vegetable growth compared to ash alone. The work contributes to the limited body of research on integrating industrial byproducts with plant growth-promoting rhizobacteria, highlighting a practical approach for sustainable soil management.

Authors' Contribution

Noor Atiqah Badaluddin: Conducted experimental work, data collection, and initial manuscript drafting.
Saiful Iskandar Khalit: Conceived and supervised the study, provided guidance on methodology, and critically revised the manuscript.
Nurnabila Kamaruzaman: Assisted with laboratory analyses, data interpretation, and literature review.
Noor Afiza Badaluddin: Contributed to experimental setup, fieldwork, and data curation.
Nornasuha Yusoff: Assisted in statistical analysis, data visualization, and manuscript editing.
Mohd Roslan Mamat: Provided technical expertise, resources, and critical review of the final manuscript.
All authors read and approved the final version of the manuscript.

Generative AI or AI assisted technology statement
The author(s) declare that no genrative AI was used in the creation of this manuscript.

Conflict of interest
The authors declared that present study was performed in absence of any conflict of interest.

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