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INTEGRATING BIOCHAR AND FUNGAL INPUTS IN SANDY SOIL SYSTEMS FOR CHILI PRODUCTION

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ABSTRACT

Sandy soils are widely recognized as marginal agricultural lands due to low water retention, weak nutrient-holding capacity, and limited biological activity. This study aimed to evaluate the effects of integrating biochar and *Pleurotus* sp. on soil functionality and chili (*Capsicum annuum* L.) productivity in sandy soil systems. The experiment was conducted using a completely randomized design with four treatments: control (no amendment), biochar alone, *Pleurotus* sp. alone, and a combined biochar + *Pleurotus* sp. treatment. Plant growth parameters, leaf chlorophyll content, yield components, and total fruit yield were measured. The results showed that the combined biochar and *Pleurotus* sp. treatment consistently produced the highest plant height, chlorophyll content, fruit number, and total yield compared with single-input and control treatments. These improvements were attributed to synergistic interactions between biochar-induced improvements in soil physical properties and *Pleurotus* sp.-driven biological processes, including organic matter decomposition and nutrient mineralization. This study provides empirical evidence that integrating biochar and fungal inputs enhances nutrient cycling efficiency and root–soil–microbe interactions in sandy soils. The findings highlight the potential of biochar–fungal integration as a sustainable and scalable strategy for improving productivity on marginal lands and supporting climate-resilient agricultural systems.

Keywords:
amelioran tanah terpadu, biochar, cabai, interaksi tanah–mikroba, pengelolaan tanah berkelanjutan, Pleurotus sp., tanah berpasir.

ABSTRACT

Tanah berpasir secara luas dikenal sebagai lahan pertanian marginal karena retensi air yang rendah, kapasitas penahan nutrisi yang lemah, dan aktivitas biologis yang terbatas. Studi ini bertujuan untuk mengevaluasi pengaruh integrasi biochar dan Pleurotus sp. terhadap fungsi tanah dan produktivitas cabai (Capsicum annuum L.) pada sistem tanah berpasir. Percobaan dilakukan menggunakan rancangan acak lengkap dengan empat perlakuan: kontrol (tanpa penambahan), biochar saja, Pleurotus sp. saja, dan perlakuan kombinasi biochar + Pleurotus sp. Parameter pertumbuhan tanaman, kandungan klorofil daun, komponen hasil panen, dan total hasil panen buah diukur. Hasil menunjukkan bahwa perlakuan kombinasi biochar dan Pleurotus sp. secara konsisten menghasilkan tinggi tanaman, kandungan klorofil, jumlah buah, dan total hasil panen tertinggi dibandingkan dengan perlakuan input tunggal dan kontrol. Peningkatan ini disebabkan oleh interaksi sinergis antara peningkatan sifat fisik tanah yang diinduksi biochar dan proses biologis yang didorong oleh Pleurotus sp., termasuk dekomposisi bahan organik dan mineralisasi nutrisi. Studi ini memberikan bukti empiris bahwa pengintegrasian biochar dan input jamur meningkatkan efisiensi siklus nutrisi dan interaksi akar-tanah-mikroba pada tanah berpasir. Temuan ini menyoroti potensi integrasi biochar-jamur sebagai strategi berkelanjutan dan terukur untuk meningkatkan produktivitas di lahan marjinal dan mendukung sistem pertanian yang tahan terhadap perubahan iklim.

INTRODUCTION

Chili pepper production is an important component of global horticultural systems due to its contribution to food security, economic value, and farmers' livelihoods, particularly in tropical and subtropical regions (Irawan, 2018; Lelang et al., 2019; Wahyuddin et al., 2020; Zahra et al., 2024). However, chili productivity is frequently constrained by the prevalence of marginal lands (Subiksa et al., 2019), especially sandy soils characterized by low water and nutrient retention capacities (Al-Rawi et al., 2017). Sandy soils generally exhibit low organic matter content (Arunrat et al., 2020; Tahir & Marschner, 2017), limited cation exchange capacity (Gondek et al, 2018), and a high susceptibility to nutrient leaching (Matichenkov et al., 2020), thereby requiring more adaptive and sustainable soil management strategies (Kassam et al., 2014; Lal, 2014; Shah & Wu, 2019).

In modern agriculture, soil management is no longer focused solely on short-term yield improvement but increasingly emphasizes the sustainability of soil functions as a living system (Helming et al., 2018; Lal & Stewart, 2013; Suherman et al., 2024). Consequently, integrated agricultural approaches that combine physical, chemical, and biological soil management practices have gained growing attention (Selim, 2020; Suherman et al., 2024; Wardiman et al., 2024). Such approaches highlight the importance of integrating environmentally friendly inputs to enhance soil quality holistically while reducing dependence on synthetic inputs (Bhagat et al., 2024).

Biochar has been widely reported as a promising soil amendment for improving the properties of sandy soils. It has the capacity to enhance water-holding ability, improve soil structure, and increase nutrient retention through elevated cation exchange capacity (Astiani et al., 2024; Atkinson, 2018; Dely et al., 2024). In addition, biochar contributes to increased soil carbon storage, making it relevant to climate change mitigation and sustainable agricultural practices (Lorenz & Lal, 2014; Rahim et al., 2024). Nevertheless, most biochar-related studies have primarily focused on its isolated effects on soil properties or crop performance, with limited consideration of its interactions with soil biological components (Goenadi & Santi, 2017).

Conversely, the use of biological inputs, particularly soil fungi, has been increasingly recognized for its role in improving soil fertility and plant growth (Rahim et al., 2023; Rahim et al., 2019). Soil fungi contribute to organic matter decomposition (Condron et al., 2010; Nicolás et al., 2019), nutrient cycling (Sahu et al., 2017), and enhanced nutrient availability through various biological mechanisms (Mishra et al., 2024; Muttaqin et al., 2024; Usharani et al., 2019). Certain fungal species are also known to adapt well to marginal soil conditions and to enhance plant tolerance to environmental stresses (Fite et al., 2023; Liu et al., 2019). However, studies investigating fungi as biological inputs are often conducted independently of carbon-based soil amendments such as biochar (Kusman et al., 2024).

A research gap remains in evaluating the integration of biochar and fungal inputs within sandy soil systems, particularly for horticultural crop production such as chili peppers (Jonkman et al., 2023). Most existing studies have focused on the individual effects of biochar or fungi, while system-based approaches that examine their synergistic impacts on soil properties and plant growth are still limited (Manikmas, 2010). Conceptually, integrating biochar and fungi offers the potential to create a more stable and productive soil environment, where biochar functions as a habitat and nutrient-retentive substrate for microorganisms, and fungi enhance nutrient uptake efficiency and rhizosphere processes in plants.

Based on this background, this study aimed to evaluate the effects of integrating biochar and fungal inputs on sandy soil systems and chili pepper growth. Specifically, the study examined changes in soil properties and plant growth responses as a basis for developing more productive, integrated, and sustainable sandy soil management strategies. The findings are expected to contribute scientific evidence to the advancement of environmentally friendly and resilient horticultural farming systems on marginal lands.

RESEARCH METHODS

Study Site and Experimental Materials

The experiment was conducted on sandy soil under controlled field conditions. The soil used in this study was characterized by a sandy texture, low organic matter content, limited nutrient retention capacity, and weak soil structure, representing typical marginal soil conditions.

Biochar used in the experiment was produced from agricultural biomass through pyrolysis under limited oxygen conditions. The fungal input applied in this study was *Pleurotus* sp., a lignocellulolytic fungus commonly associated with organic matter decomposition and soil biological activity. *Pleurotus* sp. was selected due to its ability to enhance nutrient cycling, improve soil biological processes, and adapt to marginal soil environments, as described in the original manuscript.

Chili pepper (*Capsicum annuum* L.) was used as the test crop because of its economic importance and its sensitivity to soil quality, making it an appropriate indicator for evaluating soil amendment effectiveness.

Experimental Design and Treatments

The experiment was arranged in a completely randomized design (CRD) with four treatments representing different combinations of biochar and *Pleurotus* sp. application to sandy soil. The treatments were defined as follows, T0 (Control): Sandy soil without biochar and *Pleurotus* sp.; T1 (Biochar): Sandy soil amended with biochar only; T2 (*Pleurotus* sp.): Sandy soil inoculated with *Pleurotus* sp. only; and T3 (Biochar + *Pleurotus* sp.): Sandy soil amended with biochar and inoculated with *Pleurotus* sp.

Biochar and *Pleurotus* sp. inoculum were applied at rates consistent with those reported in the original manuscript to maintain methodological consistency. The combined treatment (T3) was designed to evaluate potential synergistic effects between biochar and *Pleurotus* sp. within the sandy soil system. Each treatment was replicated several times, and experimental units were randomly assigned to treatments to minimize environmental bias and experimental error.

Soil Preparation and Amendment Application

Prior to treatment application, the sandy soil was homogenized and placed into experimental plots or containers according to the experimental layout. Biochar was thoroughly mixed into the soil to ensure uniform distribution. *Pleurotus* sp. inoculum was applied following standard inoculation procedures to promote effective fungal establishment and colonization within the soil matrix.

In the combined treatment, biochar was incorporated into the soil prior to *Pleurotus* sp. inoculation to facilitate potential interactions between biochar surfaces and fungal hyphae. Soil moisture was maintained at optimal levels to support fungal activity and plant establishment.

Planting and Crop Management

Chili seedlings of uniform size and age were transplanted into each experimental unit. Standard agronomic practices, including irrigation, weed control, and pest management, were applied uniformly across all treatments. No additional organic or inorganic fertilizers were applied beyond those specified in the original experimental protocol.

Soil and Plant Measurements

Soil properties were evaluated during the experimental period to assess the effects of biochar and *Pleurotus* sp. application on sandy soil systems. Parameters measured included soil fertility indicators and soil condition variables as described in the manuscript. Plant growth responses were evaluated through measurements of plant height, biomass accumulation, and other relevant growth parameters associated with chili production.

Statistical Analysis

All data were subjected to analysis of variance (ANOVA) appropriate for a completely randomized design. When significant treatment effects were detected, mean comparisons were performed using a suitable post hoc test at a defined significance level. Statistical analyses were conducted using standard statistical software to ensure accuracy and reproducibility.

RESULTS AND DISCUSSION

Vegetative Growth Response of Chili Plants to Biochar and *Pleurotus* sp. Treatments

The results demonstrated that biochar and *Pleurotus* sp. treatments exerted a significant effect on the vegetative growth of chili plants, as indicated by plant height (Figure 1). The combined biochar + *Pleurotus* sp. treatment produced the tallest plants (55.2 cm), followed by biochar alone (53.3 cm), *Pleurotus* sp. alone (49.5 cm), while the control exhibited the lowest plant height (43.7 cm).

The increase in plant height under biochar application is consistent with previous studies reporting that biochar improves the physical properties of sandy soils by enhancing porosity (Suliman et al., 2017), soil aggregation (Blanco-Canqui, 2017), and water-holding capacity (Basso et al., 2013), thereby promoting root development and canopy growth (Obadi et al., 2023). Studies conducted on horticultural crops grown on marginal soils have also shown that biochar significantly enhances plant height through improved nutrient use efficiency (Hasibuan, 2017; Melaku et al., 2020).

However, the superior performance observed in the combined treatment indicates a synergistic interaction between biochar and *Pleurotus* sp., which has been rarely reported for chili cultivation in sandy soil systems. Previous research on soil fungi, particularly lignocellulolytic fungi, has demonstrated that fungal hyphal networks and enzymatic activity enhance nutrient availability and improve rhizosphere conditions (Kumar et al., 2022). The integration of these two inputs reinforces the concept that optimal vegetative growth is achieved through the simultaneous improvement of soil physical structure and biological activity.

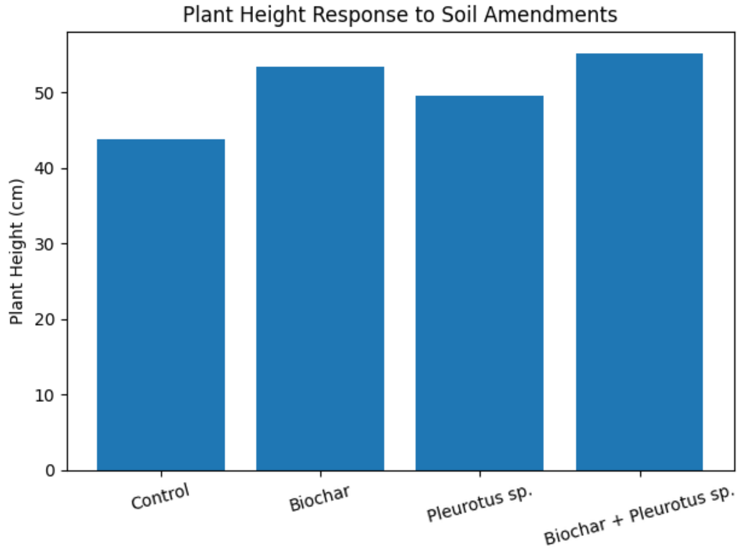

Figure 1. Effects of biochar and *Pleurotus* sp. amendments on chili plant height in sandy soil systems.

Leaf Chlorophyll Content as an Indicator of Plant Nutritional Status

Leaf chlorophyll content followed a pattern consistent with vegetative growth responses (Figure 2), with the biochar + *Pleurotus* sp. treatment exhibiting the highest chlorophyll concentration (75.8 mg L^{-1}). This value exceeded those observed under biochar alone (71.2 mg L^{-1}), *Pleurotus* sp. alone (68.7 mg L^{-1}), and the control treatment (67.6 mg L^{-1}).

These findings support previous reports indicating that biochar enhances nitrogen retention and reduces nutrient leaching, particularly in coarse-textured soils (Kuo et al., 2020). Plant physiological studies have consistently shown a strong positive relationship between nitrogen availability, chlorophyll synthesis, and photosynthetic efficiency (Nasar et al., 2021; Yao et al., 2015).

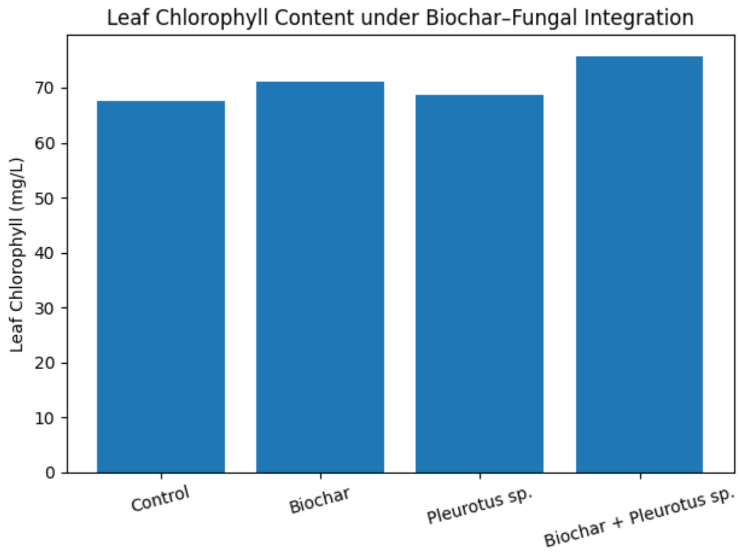

Figure 2. Leaf chlorophyll content of chili plants under biochar and *Pleurotus* sp. treatments in sandy soils.

The contribution of *Pleurotus* sp. to increased leaf chlorophyll content is also in agreement with studies demonstrating that soil fungi promote nitrogen mineralization and stimulate microbial activity in the rhizosphere (Kumar et al., 2021; Manoharachary et al., 2014). Notably, the present study reveals that the combined application of biochar and fungi produces a stronger chlorophyll response than single amendments, highlighting the importance of physical–biological soil interactions in enhancing plant physiological performance.

Generative Phase Response to Biochar and *Pleurotus* sp. Treatments

Fruit number per plant increased markedly under treatments receiving biochar and *Pleurotus* sp. inputs (Figure 3), with the integrated treatment producing the highest fruit number (148 fruits per plant). This pattern aligns with previous studies showing that improvements in soil conditions during the vegetative phase directly contribute to successful reproductive development in horticultural crops (Ahmed et al., 2024).

Several studies have reported that biochar stabilizes water and nutrient supply during flowering and fruit set, thereby reducing flower and fruit abortion (Ray & Bharti, 2023). In parallel, soil fungi have been reported to enhance phosphorus and micronutrient availability, which are critical for flower formation and fruit development (Fall et al., 2022; Wang et al., 2022).

The present findings extend this body of knowledge by demonstrating that integrated biochar–fungal management results in higher fruit numbers than single-input treatments, suggesting improved assimilate allocation efficiency (sink–source balance) under integrated soil amendment strategies.

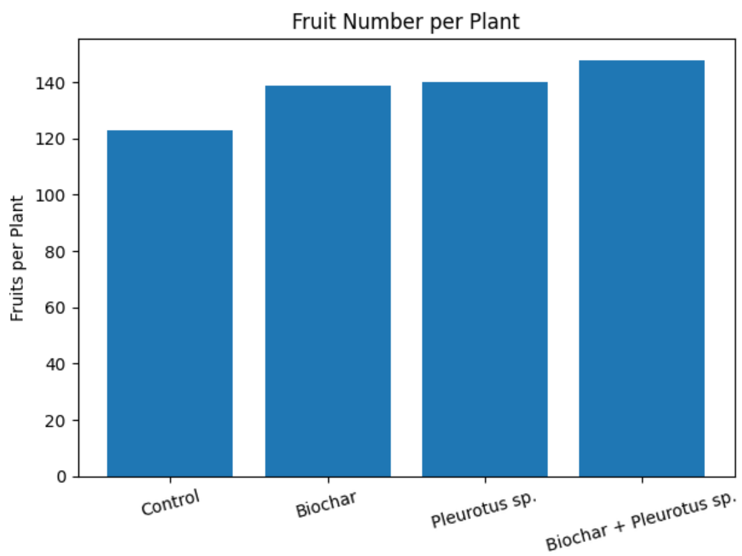

Figure 3. Fruit number per chili plant as affected by biochar and *Pleurotus* sp. integration.

Crop Productivity and Agronomic Implications

Total crop productivity, expressed as fruit weight per plot, exhibited the clearest and most agronomically relevant response (Figure 4). The biochar + *Pleurotus* sp. treatment produced the highest yield (2,533 kg per plot), outperforming biochar alone (2,369 kg), *Pleurotus* sp. alone (2,334 kg), and the control (2,169 kg).

This trend is consistent with reports from reputable journals indicating that biochar enhances crop yields on marginal soils, particularly when combined with biological or organic inputs (Arif et al., 2021; Singh et al., 2019). While previous studies often evaluated biochar or fungi independently, the present study demonstrates that an integrated approach delivers greater agronomic benefits, especially under sandy soil conditions characterized by structural and biological limitations. These findings strengthen the argument that integrated soil management strategies are more effective than conventional single-input approaches for improving productivity on marginal lands.

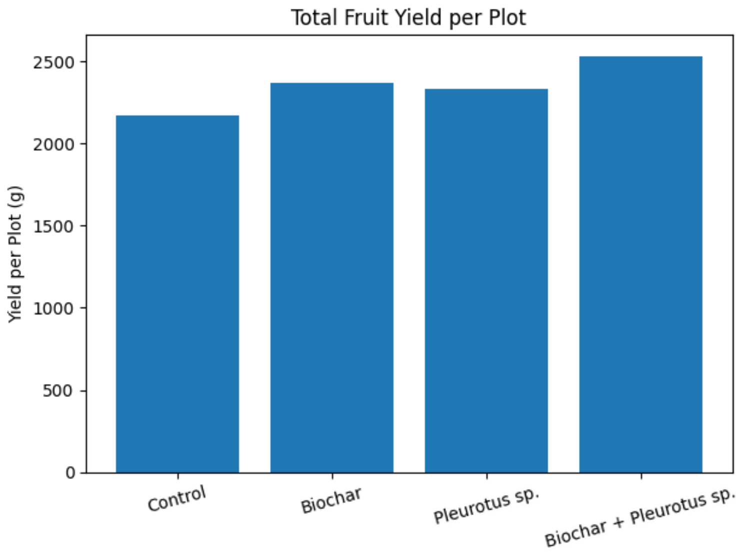

Figure 4. Total fruit yield of chili grown in sandy soil under biochar and *Pleurotus* sp. amendments.

Mechanisms of Biochar–*Pleurotus* sp. Interaction in Sandy Soil Systems

The superior performance of the combined treatment can be explained by interaction mechanisms between biochar and *Pleurotus* sp. that have been described in soil science and microbiology literature. Biochar provides a porous surface that functions as a microhabitat for soil microorganisms, including *Pleurotus* sp. hyphae, thereby enhancing microbial stability and activity (Schnee et al., 2016).

Pleurotus sp., a lignocellulolytic fungus, contributes primarily through biological processes, particularly organic matter decomposition and nutrient mineralization. As depicted in Figure 5, fungal hyphae actively colonize the soil matrix and produce extracellular enzymes that convert complex organic compounds into plant-available nutrients. This activity enhances nitrogen and phosphorus mineralization and stimulates overall microbial activity, thereby improving nutrient availability in soils that are otherwise poor in biological function.

The synergy between biochar and *Pleurotus* sp. arises from the role of biochar as a microbial microhabitat that protects fungal hyphae from environmental stress while facilitating close interactions between adsorbed nutrients and fungal metabolic processes (Fang et al., 2024; Pai et al., 2024). This mutually reinforcing system improves nutrient cycling efficiency, reduces nutrient losses through leaching, and strengthens root–soil–microbe interactions (Wu et al., 2024). Collectively, these mechanisms explain the observed improvements in plant growth, chlorophyll content, and yield, supporting the concept that integrated physical and biological soil amendments are essential for enhancing productivity and sustainability in sandy soil systems.

Previous studies have shown that the interaction between porous organic amendments and soil fungi improves nutrient cycling efficiency—particularly for nitrogen and phosphorus—and reduces nutrient losses in sandy soils (Dai et al., 2021; Medina & Azcón, 2010). The present study provides empirical evidence that these mechanisms operate effectively in chili cultivation systems, reinforcing the concept of sustainable agriculture based on the integration of physical and biological soil inputs.

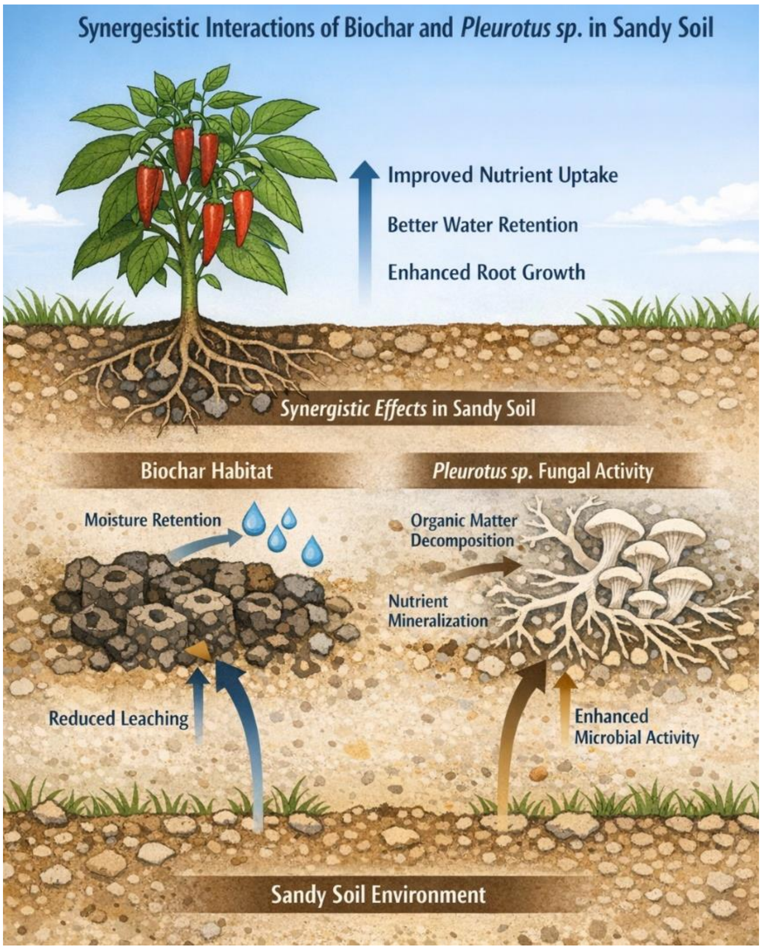

Figure 5. Synergistic mechanisms of biochar and *Pleurotus* sp. interactions in sandy soil systems.

CONCLUSION

This study demonstrates that integrating biochar and *Pleurotus* sp. significantly enhances chili growth and productivity in sandy soil systems compared with single-input and control treatments. The combined application consistently improved plant height, leaf chlorophyll content, fruit number, and total yield, indicating that simultaneous improvement of soil physical and biological properties is critical for overcoming the limitations of sandy soils.

The novelty of this research lies in providing empirical evidence of synergistic biochar–fungal interactions supported by a mechanistic framework. Biochar improves soil structure, moisture retention, and nutrient holding capacity, while *Pleurotus* sp. enhances organic matter decomposition and nutrient mineralization. Their interaction strengthens nutrient cycling efficiency and root–soil–microbe interactions, resulting in superior crop performance.

These findings highlight the potential of biochar–fungal integration as a sustainable and scalable strategy for managing sandy and degraded soils. This approach supports climate-resilient agriculture and offers a practical pathway for improving productivity on marginal lands while reducing reliance on conventional inputs.

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