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# Enhancing Switchgrass Growth With Biochar Derived From Mushroom Residue: A Study on Regulating Physicochemical Properties of Acidic Phosphogypsum

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**Keywords:** ameliorant effect | biochar | mushroom residue | phosphogypsum | switchgrass

## ABSTRACT

Acidity limits plant growth, particularly when the growing medium has a pH below 5, a challenge that is particularly relevant for certain plants like switchgrass (*Panicum virgatum*). Although adding biochar to the growing medium has been shown to improve plant growth by modulating acidity, its specific impact on switchgrass remains largely uninvestigated. Thus, we conducted a pot experiment to assess how different biochar application rates (0%, 1%, 2.5%, 5%, 10%, and 20% w/w), derived from mushroom residue through muffle furnace pyrolysis at 350°C for 2 h, affect the physicochemical attributes of phosphogypsum and subsequent switchgrass growth. Our findings revealed that adding biochar to phosphogypsum significantly alleviated acidity and enhanced moisture, organic matter, total nitrogen, total phosphorus, total potassium, available phosphorus, and available potassium contents. Notably, the 10% biochar treatment had the most positive impacts on germination rates, while the 5% treatment had the greatest improvements in shoot length, tiller number, and total weight compared to the control. Structural equation modeling illustrated that biochar indirectly contributed to switchgrass health by altering the physicochemical properties of phosphogypsum, with pH as the pivotal regulator. Our study demonstrated the potential of mushroom residue biochar as an effective amendment for acidic substrates/matrix (e.g., soil), offering a promising strategy to improve physicochemical conditions and stimulate plant growth.

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Yangzhou Xiang and Yanting Mao contributed equally to this work.

## 1 | Introduction

Phosphogypsum is a byproduct of phosphorus extraction from phosphate rock using a wet-process phosphoric acid method (Bouargane et al. 2023). This process typically generates 4–5 tons of phosphogypsum for every 1 ton of phosphoric acid produced (Chen et al. 2022). The main component of phosphogypsum is $CaSO_4 \cdot 2H_2O$, but it also contains harmful substances such as fluorine, mercury, heavy metals, and radioactive elements (Tayibi et al. 2009). With an annual global production of around 300 million tons (Bilal et al. 2023), there is growing attention towards using phosphogypsum (Cao et al. 2022) as a raw material for construction materials (Huang et al. 2022; Jin et al. 2023; Wu et al. 2022), composting (Lei et al. 2021; Yang et al. 2022), and soil amendment to increase crop and wood production (Bossolani et al. 2022; Crusciol et al. 2016; de Sousa et al. 2022). Surprisingly, only 14% of phosphogypsum is recycled, with 28% discharged into the sea and 58% stored in piles (Bilal et al. 2023). The accumulation of phosphogypsum stockpiles has led to environmental issues (Qin et al. 2023), such as soil and water pollution from phosphogypsum leachate (Jalali et al. 2019; Millán-Becerro et al. 2023). Furthermore, phosphogypsum-derived building materials might pose radioactive risks to human health (Al-Hwaiti et al. 2014), and using phosphogypsum as a soil amendment could result in the accumulation of heavy metals and other harmful substances in crops, threatening food safety (Al-Hwaiti and Al-Khashman 2015; Peng et al. 2020).

The increasing global demand for phosphoric acid has expanded the regions affected by phosphogypsum pollution (Turner et al. 2022), emphasizing the need for environmentally friendly in situ treatment methods. Previous studies have shown that bacteria in phosphogypsum-contaminated soil can promote plant growth (Boldt-Burisch and Anne 2019; Jalali et al. 2020), and various plants like trees and grasses, lichens, and mosses can establish on long-term open-air stacks of phosphogypsum (Boldt-Burisch et al. 2023; Gázquez et al. 2014; Jalali et al. 2019). In the pursuit of natural restoration, Robinson et al. (2023) used soil caps (15 cm thick) and fast-growing *Salix* and *Populus* species to create a protective layer on the surface of phosphogypsum stacks to mitigate environmental impacts. Likewise, Turner et al. (2022) recommended soil capping depths ≥ 15 cm and *Agropyron trachycaulum* and *Festuca ovina* for reclaiming phosphogypsum deposition sites. However, the high cost of soil capping remediation is not suitable for large areas of phosphogypsum stacks.

Biochar, derived from pyrolyzed biomass, is nutrient-rich and offers the potential for carbon neutralization (Hagemann et al. 2017; Xia et al. 2024; Xiang et al. 2023). Biochar, with it high surface area, porosity, and pH, has been successfully used in the ecological restoration of acid mines (Novak et al. 2018; O'Connor et al. 2018; Shetty et al. 2021) and has shown promise in improving soil functions, immobilizing heavy metals and promoting plant growth and crop production (Tang et al. 2020; Wang et al. 2023; Zhang et al. 2024). Biochar is considered a low-cost and environmentally friendly measure for mine remediation (Alhar, Thompson, and Oliver 2021; Azeem et al. 2021). Switchgrass (*Panicum virgatum*), known for its heavy metal accumulation and tolerance, is commonly studied in mine management (Novak et al. 2019; Patra et al. 2021; Rylott and Bruce 2022) and biofuel production (McLaughlin and Adams Kszos 2005; Sainju and Allen 2023). Despite its potential, only a few reports in the literature investigate the physicochemical effects of biochar-enhanced phosphogypsum on switchgrass cultivation.

To address this research gap, we conducted a pot experiment with switchgrass planted on phosphogypsum substrate amended with mushroom residue biochar. Our objectives were to (1) determine whether mixing biochar with phosphogypsum influences switchgrass growth; (2) explore how biochar affects the physical and chemical properties of phosphogypsum substrate; (3) identify the optimal biochar dosage for enhancing phosphogypsum to optimize switchgrass growth; (4) examine how biochar regulates phosphogypsum substrate characteristics to drive switchgrass growth using a structural equation model.

## 2 | Materials and Methods

### 2.1 | Experimental Material Collection and Preparation

Switchgrass variety 'Blackwell,' obtained from China Agriculture University, was used for this experiment. Phosphogypsum was sourced from Fuquan City (26°41′11″ N, 107°31′13″ E), Guizhou Province. After natural air drying and before passing the phosphogypsum through a 2 mm nylon sieve, the phosphogypsum impurities were manually separated using tweezers and a fine brush. Mushroom residue collected from the edible mushroom park in Qinglong County, southwest China, consisted of 50% sawdust, 30% corncob, and 20% wheat bran. Mushroom residue biochar was produced in the following steps: removal of plastic and other impurities → drying → crushing → pyrolysis at 350°C in a muffle furnace for 2 h → natural cooling → storage in a self-sealing bag with proper labeling.

### 2.2 | Experimental Design

The experiment was conducted in a plastic greenhouse at Guizhou Education University, Guizhou Province, China (106.80° E, 26.65° N) from March to July 2022. The experiment had a completely randomized design with six treatments and three replications involving different levels of mushroom residue biochar: 0% biochar, 1% biochar, 2.5% biochar, 5% biochar, 10% biochar, and 20% biochar (referred to as 0% biochar, 1% biochar, 2.5% biochar, 5% biochar, 10% biochar, and 20% biochar, respectively). Eighteen plastic pots (11.5 cm tall × 20.5 cm upper diameter × 9.5 cm lower diameter; Jiuqiangu Horticulture Company, China) were filled with 1 kg of substrate comprising a mixture of phosphogypsum and biochar (Table 1; Figure 1). After preparing the composite substrate, it was gradually watered to reach about 70% of its moisture content and left for 48 h. Switchgrass seeds were sterilized with 75% ethanol for 5 min, washed three times with deionized water, and then soaked in deionized water for 12 h.

**TABLE 1** | Physicochemical properties of phosphogypsum and mushroom residue biochar.

| Properties | Phosphogypsum | Mushroom residue biochar |
|---|---|---|
| Bulk density ($g\,cm^{-3}$) | 0.47 | 0.68 |
| Moisture (%) | 5.22 | — |
| pH | 4.19 | 9.89 |
| Organic carbon ($g\,kg^{-1}$) | 0.95 | 518.62 |
| Total nitrogen ($g\,kg^{-1}$) | 0.53 | 12.49 |
| Total phosphorus ($g\,kg^{-1}$) | 8.79 | 7.50 |
| Total potassium ($g\,kg^{-1}$) | 12.08 | 69.08 |
| Available nitrogen ($mg\,kg^{-1}$) | 63.05 | — |
| Available phosphorus ($mg\,kg^{-1}$) | 578.68 | — |
| Available potassium ($mg\,kg^{-1}$) | 4.19 | — |

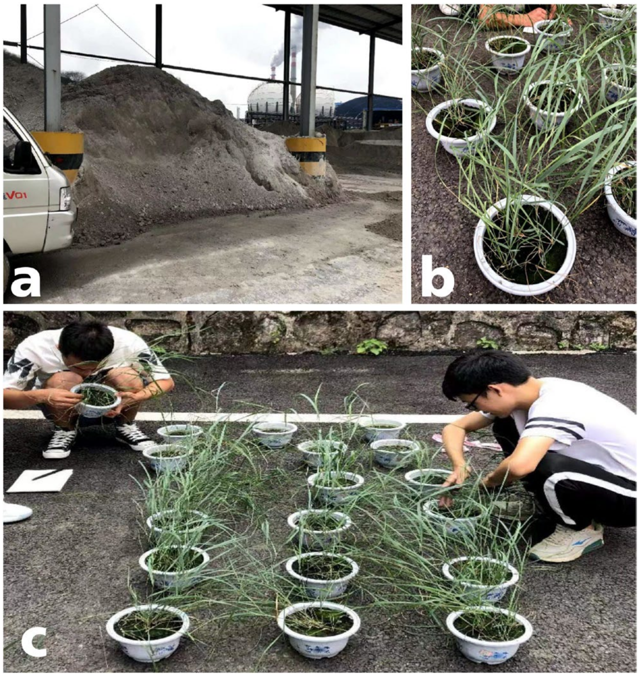

**FIGURE 1** | Overview of experimental procedures and measurements. (a) Collection of phosphogypsum from a local factory; (b) pots with varying concentrations of mushroom residue biochar mixed into phosphogypsum; (c) measuring key plant traits such as shoot length, tiller number, and total weight.

Twenty seeds were sown in each pot at 1 cm depth. Daily observations and watering were carried out during switchgrass growth.

## 2.3 | Measurements

The germination rate was determined as the ratio of germinated seeds to the total number of seeds sown and was assessed 14 days after sowing Boykov, Shuford, and Zhang (2019). Shoot length, tiller number, and total weight of switchgrass were measured 90 days after sowing. The length of the longest shoot for each individual switchgrass plant in each pot was measured using a metric scale (cm), with average lengths calculated for each pot (Awoyemi and Dzantor 2017). Tiller number was counted from the base of switchgrass stems on all switchgrass plants in each pot and then averaged (Zhao et al. 2023). For biomass harvesting, dust on the plant's surface and impurities in the roots were removed by rinsing with clean water and then deionized water three times before oven drying at 105°C for about 30 min and then 85°C until constant weight. The total weight (shoots + roots) of switchgrass plants in each pot was measured using an electronic scale with 0.01 g precision.

## 2.4 | Physicochemical Analysis of Phosphogypsum and Mushroom Residue Biochar

Before the experiment, three replicates of phosphogypsum and mushroom residue biochar were sampled for physicochemical analyses (Table 1).

Before harvesting the switchgrass plants, we collected samples of the biochar-phosphogypsum composite substrate using a 200 $cm^3$ ring knife. These samples were oven-dried at 105°C to constant weight using an electronic balance scale with 0.01 g precision. The bulk density ($g\,cm^{-3}$) was calculated by dividing the substrate dry weight by 200. After harvesting the switchgrass plants, we sampled the biochar-phosphogypsum composite substrate from all pots. These samples were air-dried and ground to pass through a 2 mm sieve, removing plant tissue for physicochemical properties determination. An electronic pH meter was used to measure substrate pH in a 1:2.5 (v:w) water-to-soil dilution (Dong et al. 2022). To measure the substrate's dry weight (DW), 50 g of fresh substrate (FW) was placed in an aluminum box and oven-dried at 105°C to constant weight. Substrate moisture was calculated as follows (Mao et al. 2022): substrate moisture (%) = (FW–DW)/DW × 100. The chemical properties of phosphogypsum, biochar, and biochar-phosphogypsum composite substrates were determined as follows Bao (2008): organic matter using high-temperature external thermal potassium dichromate oxidation-volumetric method, total nitrogen (N) using the Kjeldahl method, total phosphorus (P) using the molybdenum antimony colorimetric method, total potassium (K) using the NaOH melting-flame spectrophotometry, available N using the alkali solution diffusion method, available P using 0.5 $mol\,L^{-1}$ sodium carbonate extraction-molybdenum antimony spectrophotometry, and available K using ammonium acetate extraction-flame spectrophotometry.

## 2.5 | Statistical Analysis

One-way analysis of variance (ANOVA) was used to determine the impacts of biochar on substrate properties and switchgrass growth characteristics. The least significant difference (LSD) test examined significant differences between treatments at a 95% confidence level. The statistical analyses were performed in R statistical software (R version 4.3.0, R Core Team, Vienna, Austria). Graphs were generated using Origin 2023 software (Origin Lab, USA). The data in the column graphs are presented as the mean ± standard deviation.

Mantel tests with 999 permutations were used to evaluate the relationships between switchgrass growth characteristics and substrate properties, utilizing the 'ggClusterNet' and 'tidyverse' packages in R (Wen et al. 2022). To overcome the limitations of correlation analysis, which cannot simultaneously assess the relationships between multiple associated factors (Nan et al. 2022), we employed Structural Equation Modeling (SEM). SEM was conducted to assess the direct and indirect effects of biochar rate and growth substrate properties on the germination rate, shoot length, tiller number, and total weight of switchgrass. This approach allowed us to understand the contributions of specific latent variables in a more comprehensive manner. For the SEM analysis, we used AMOS 22.0 software (Amos Development Co., USA) (Shen et al. 2022).

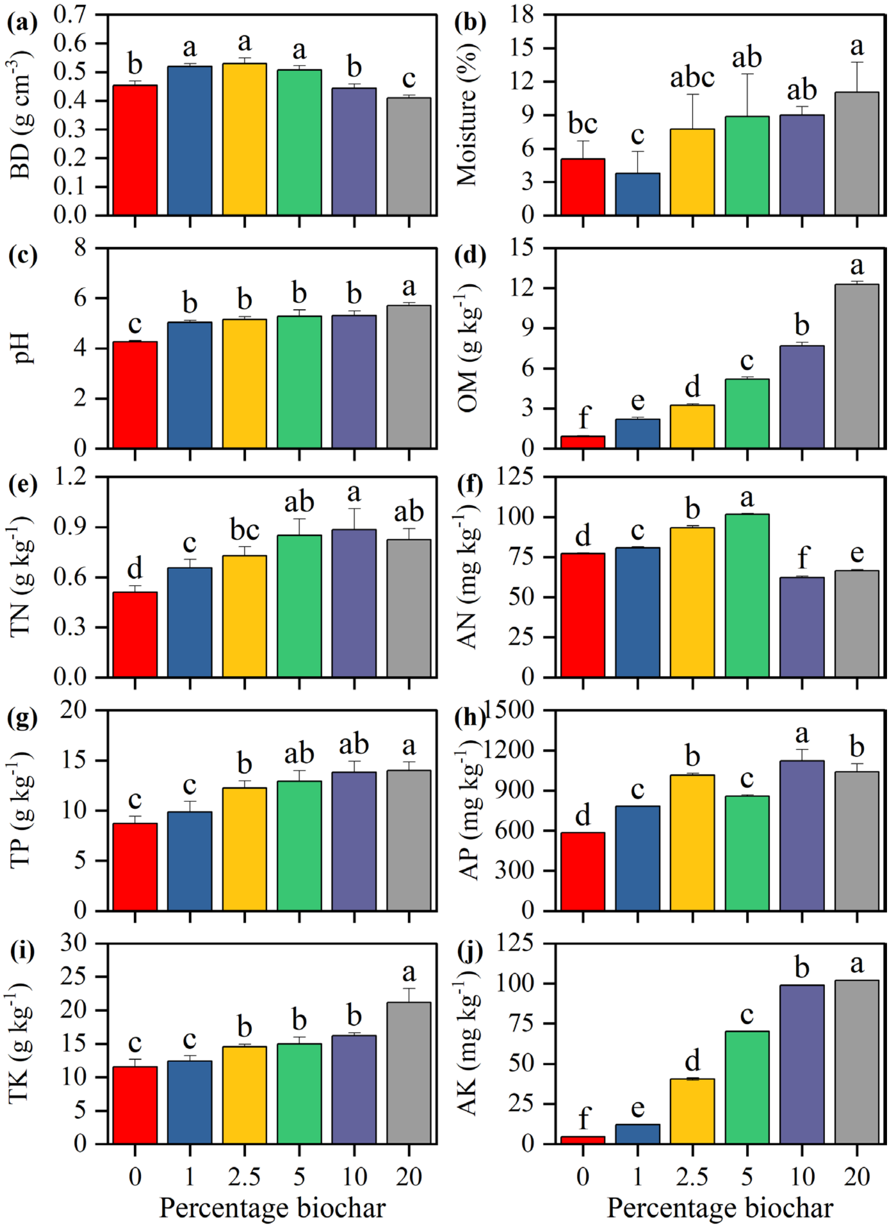

**FIGURE 2** | Effect of mushroom residue biochar on the physicochemical properties of phosphogypsum substrate. Physicochemical properties include a, BD, bulk density; b, water content; c, pH; d, OM, organic matter; e, TN, total nitrogen; f, AN, available nitrogen; g, TP, total phosphorus; h, AP, available phosphorus; i, TK, total potassium; j, AK, available potassium. The *x*-axis represents "percentage biochar" (0, 1, 2.5, 5, 10, and 20), indicating the percentage of biochar applied to the substrate. Different lowercase letters above the error bars indicate significant differences ($p < 0.05$) among treatments.

# 3 | Results

## 3.1 | Effects of Biochar on Phosphogypsum Substrate Properties

Biochar application significantly affected the properties of the phosphogypsum substrate. The bulk density of phosphogypsum substrate significantly increased with 1%–5% biochar additions ($p < 0.05$, Figure 2) and significantly decreased with 20% biochar addition ($p < 0.05$, Figure 2a) compared with the control. Conversely, the water content of the phosphogypsum substrate significantly increased with 20% biochar addition ($p < 0.05$), with no significant effect for the other biochar additions compared to the control (Figure 2b).

The pH and organic matter, total P, total K, and available K contents of the phosphogypsum substrate systematically increased with increasing biochar addition (Figure 2c,d,g,i,j). All biochar treatments significantly increased the pH and organic matter, total N, available P, and available K contents of the phosphogypsum substrate ($p < 0.05$) compared to the control. Treatments with more than 2.5% biochar addition significantly increased total P and total K contents in the phosphogypsum substrate ($p < 0.05$) compared to the control. Notably, the available N content of the phosphogypsum substrate exhibited an initial increase (up to 5% biochar) but decreased with further biochar addition ($p < 0.05$). This trend indicated an optimal dosage of 5% biochar to achieve the maximum available N content in the phosphogypsum substrate (Figure 2f).

## 3.2 | Effects of Biochar on Switchgrass Growth Characteristics

In the control treatment, switchgrass did not germinate due to the low pH of pure phosphogypsum substrate (Figure 3). The switchgrass germination rate increased with increasing biochar addition ($p < 0.05$), peaking at 81.67% with 10% biochar addition (Figure 3a).

Shoot length, tiller number, and total weight of switchgrass exhibited an initial increase followed by a subsequent decrease with increasing biochar application rate (Figure 3b–d). Moreover, 5% biochar addition produced significantly greater shoot length, tiller number, and total weight of switchgrass than the other biochar treatments ($p < 0.05$).

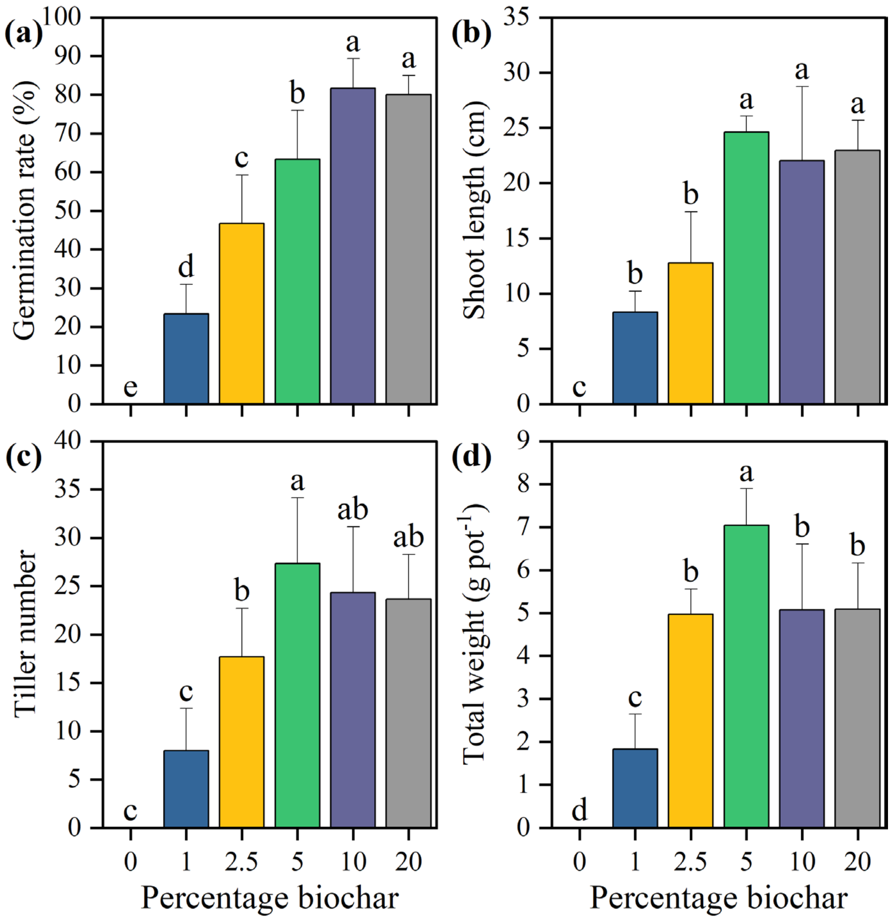

**FIGURE 3** | Effect of mushroom residue biochar on the growth characteristics (a, germination rate; b, shoot length; c, tiller number; and d, total weight) of switchgrass cv. Blackwell. The *x*-axis represents "percentage biochar" (0, 1, 2.5, 5, 10, and 20), indicating the percentage of biochar applied to the substrate. Different lowercase letters above the error bars indicate significant differences ($p < 0.05$) among treatments.

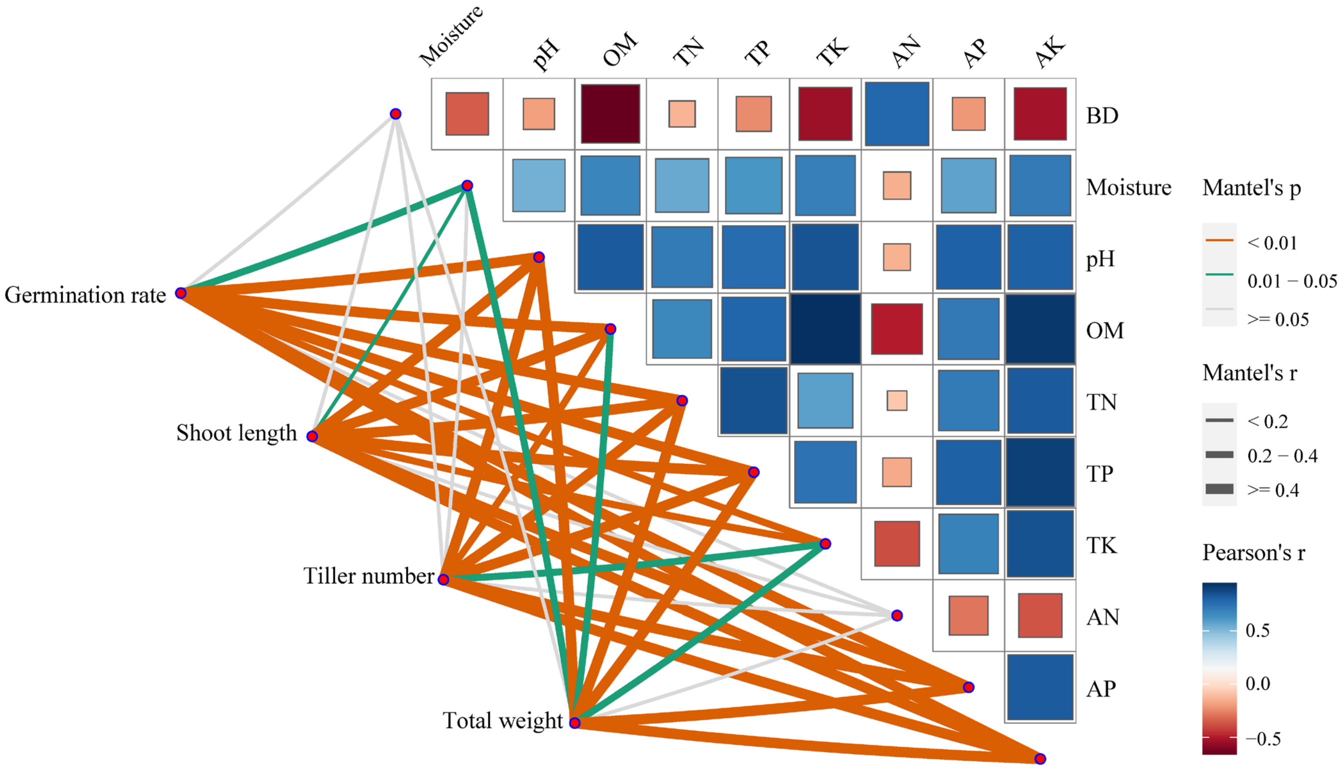

**FIGURE 4** | Correlations between switchgrass traits (germination rate, shoot length, tiller number, total weight) and growth substrate properties (AK, available potassium; AN, available nitrogen; AP, available phosphorus; BD, bulk density; SOM, soil organic matter; TK, total potassium; TN, total nitrogen; TP, total phosphorus). Edge widths correspond to Mantel's *r*-values, with edge color denoting statistical significance. Pairwise correlations between these variables are color-coded based on Pearson's correlation coefficients.

### 3.3 | Relationship Between Switchgrass Traits and Growth Substrate Properties

The Mantel test was used to explore the key substrate properties that distinguished germination rate, shoot length, tiller number, and total weight of switchgrass among the six biochar treatments (Figure 4). The analysis revealed that the growth substrate's pH and total N, total P, available P, and available K contents significantly correlated with germination rate, shoot length, tiller number, and total weight of switchgrass ($p < 0.01$). Moreover, the organic matter content of the growth substrate significantly shaped the germination rate, shoot length, and tiller number of switchgrass ($p < 0.01$), and the total K content of the growth substrate significantly regulated the germination rate and shoot length of switchgrass ($p < 0.01$). Four switchgrass traits were not associated with the bulk density or available N content of the growth substrate ($p > 0.05$).

Notably, the SEMs indicated that 73% of the variation in switchgrass germination rate was directly attributed to the growth substrate's moisture and pH levels, with the growth substrate's pH the most significant indicator ($p < 0.001$, $\beta = 0.70$) (Figure 5a). Moreover, the growth substrate's moisture, total P, and pH levels were collectively explained 75% of the variation in switchgrass shoot length, with the growth substrate's pH the most significant predictor ($p < 0.01$, $\beta = 0.51$) (Figure 5c). The modeling results showed that 71% of the variation in switchgrass tiller number was directly explained by the total N content, pH, and available P content of the growth substrate, with available P content being the most crucial predictor ($p < 0.05$, $\beta = 0.47$) (Figure 5e). The SEM results further indicated that total P content, pH, and available N content of the growth substrate directly explained 83% of the variation in switchgrass total weight (Figure 5g), with total P content the strongest causative factor ($p < 0.001$, $\beta = 0.53$), followed by pH ($p < 0.01$, $\beta = 0.44$). The SEMs did not detect any significant and direct effects of biochar rate on switchgrass germination rate, shoot length, tiller number, or total weight (Figure 5b,d,f,h).

## 4 | Discussion

### 4.1 | Impact of Biochar on Phosphogypsum Substrate Properties

Our investigation revealed that adding mushroom residue biochar enhanced the pH level of the acidic phosphogypsum substrate. Specifically, a 20% biochar application rate increased pH by 1.44 units relative to the control (Figure 2c). Similarly, Jain et al. (2020) demonstrated that adding biochar derived from lemongrass waste (4%) to highly acidic mine waste (pH = 2.84) increased pH by 1.82 units after 90 days. In another study, Xu et al. (2014b) reported that adding 5% rice straw-derived biochar to acidic soil (pH = 4.48) increased pH by 1.61 units. These increases in pH can be attributed to biochar's alkaline nature

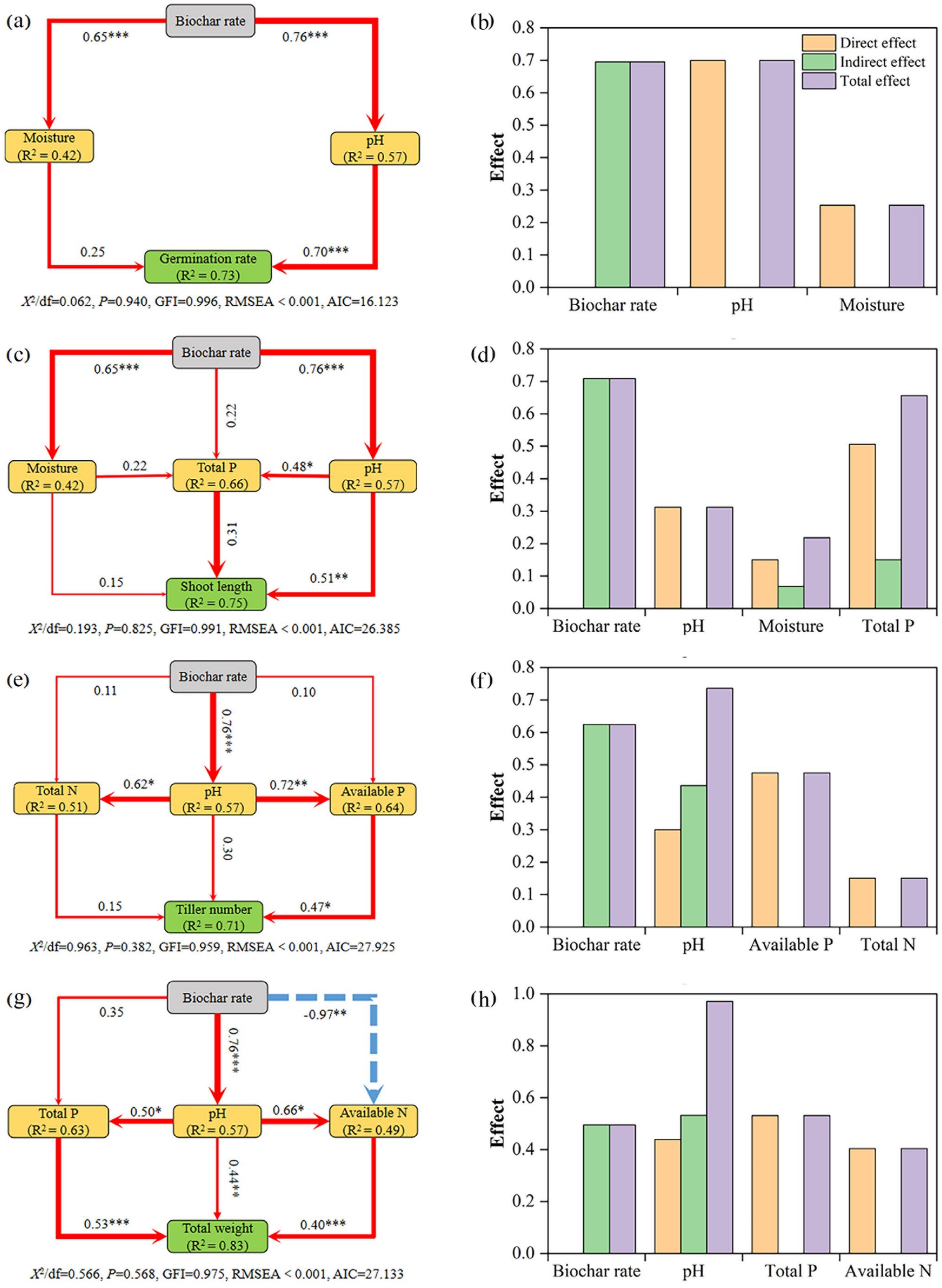

**FIGURE 5** | Legend on next page.

**FIGURE 5** | Structural equation models showing the direct and indirect effects of biochar rate and growth substrate properties on switchgrass growth. Numbers adjacent to the arrows represent path coefficients, with arrow width proportional to the strength of each coefficient. Red solid arrows indicate positive paths ($p < 0.05$), blue solid arrows indicate negative paths ($p < 0.05$), and black dotted arrows indicate nonsignificant paths ($p > 0.05$). ***, **, * indicate significance at $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively. $R^2$ denotes the proportion of variance explained by the predictors. The right-hand panels (b/d/f/h) display standardized effects derived from the structural equation model, with the $y$-axis representing standardized coefficients on an arbitrary scale, facilitating comparison across variables.

and rich content of specific functional groups (Bolan et al. 2023; Shetty and Prakash 2020; Xia et al. 2020), such as carbonates and functional groups such as-COO and O- (Jain et al. 2020; Yuan, Xu, and Zhang 2011). However, it is important to note that variations in biochar type and substrate properties can lead to varying changes in pH (Chintala et al. 2014; Wang et al. 2014; Yan et al. 2021).

In addition to pH, our findings indicate that mushroom residue biochar increased the total N content in the phosphogypsum substrate (Figure 2e), corroborating similar findings from pot experiments (Xia et al. 2020; Xu et al. 2014a, 2014b; Yan et al. 2021), and could be because biochar reduced total N losses by inhibiting ammonia ($NH_3$) volatilization and nitrous oxide ($N_2O$) emissions in acidic soil (Li et al. 2019; Wang et al. 2017; Zhang et al. 2021). Numerous studies have examined the effect of biochar on available N content in acidic substrates (Jin et al. 2019; Xia et al. 2020; Yan et al. 2021), with some contradictory results. For example, increasing wheat straw biochar application to soil with pH 4.24 significantly increased ammonium and nitrate contents (Jin et al. 2019), whereas increasing peanut shell biochar addition to soil with pH 4.40 gradually decreased available N content (Xia et al. 2020). We also observed a complex relationship between biochar and available N in phosphogypsum substrate, where available N increased initially and then decreased with increasing mushroom residue biochar addition (Figure 2f). Ghosh, Masto, and Maiti (2020) reported similar results. The promoting effect under lower biochar loadings is likely due to plant root absorption and utilization of available N, reducing the ability of biochar to supply mineral N (Jin et al. 2019); however, under conditions of higher biochar application rates, the absorption of available N by plant roots exceeded the amount provided by the substrate, leading to a reduced growth effect (Xia et al. 2020).

Moreover, our findings demonstrate that adding biochar to the phosphogypsum substrate increased total P, available P, total K, and available K contents, aligning with previous studies that found biochar application to acidic soil enhanced the total amount and availability of P and K (Berihun, Tadele, and Kebede 2017; Jin et al. 2019; Xia et al. 2020). These positive effects of biochar on P could be attributed to (1) alkaline biochar application enhancing P desorption in acidic soil by increasing soil pH and altering phosphate sorption capacity by metal ions such as $Al^{3+}$, $Fe^{3+}$, and $Ca^{2+}$ in soil (Xu et al. 2014a; Yang and Lu 2022; Zhou et al. 2020), (2) biochar releasing P into the substrate (Jin et al. 2019; Piash, Iwabuchi, and Itoh 2022), or (3) biochar addition to acidic soil improving the soil environment and increasing microbial activities, promoting soil organic P mineralization (Kannan et al. 2021; Tian et al. 2021). The promoting effects of biochar on K in acidic soil could be attributed to (1) biochar directly increasing the K content of the acidic substrate (Berihun, Tadele, and Kebede 2017; Xia et al. 2020), (2) biochar's high cation exchange capacity preventing K leaching into acidic soil (Bilias et al. 2023), or (3) biochar enriching the K availability in acidic soil by increasing the activity of K-dissolving bacteria, such as *Azotobacter* and *Pseudomonas* (Zhang et al. 2022).

### 4.2 | Impact of Biochar on Switchgrass Growth

Our study confirmed that adding mushroom residue biochar to phosphogypsum substrate increased the switchgrass germination rate with increasing biochar rate (Figure 3a), consistent with previous studies (Das, Ghosh, and Avasthe 2020; Ghosh, Masto, and Maiti 2020). Raw phosphogypsum has strong acidity and low moisture retention capacity (Elfadil et al. 2020), rendering it unsuitable for switchgrass germination. Liu and Lal (2013) also demonstrated that low soil pH may hinder seed germination. Our SEM results suggest that mushroom residue biochar directly regulated pH and moisture levels in the phosphogypsum substrate, improving switchgrass germination (Figure 5a).

Furthermore, our study demonstrated that switchgrass shoot length, tiller number, and total weight initially increased and then decreased with increasing mushroom residue biochar, with the highest performance at 5% biochar (Figure 3b–d). These results align with other studies (Mohamed et al. 2017; Uslu et al. 2020), but the mechanisms behind these effects on plant growth varied due to biochar's interactions with the phosphogypsum substrate. Wan et al. (2018) reported that P addition increased the plant height of *Solidago canadensis*. Thus, the improved switchgrass shoot length could be attributed to P supplementation enhancing leaf uptake of mineral elements such as Zn and Fe (Bouras et al. 2022).

Switchgrass shoot biomass increased with the increased moisture under biochar addition (Hansen et al. 2016; Reyes-Cabrera et al. 2017). Our study showed that mushroom residue biochar increased switchgrass shoot length mainly by reducing phosphogypsum acidity, thereby promoting total P and moisture contents (Figure 3b). Chen et al. (2021) also reported that biochar promoted rice shoot length.

The biochar-mediated increase in the number of switchgrass tillers was indirectly driven by the regulation of available P content, pH, and total N content (Figure 3c). Similarly, research on other plant species such as wheat Solaiman et al. (2010), *Saccharum spontaneum* (Cummings, Parker, and Gilbert 2023), and *Panicum maximum* (Almeida et al. 2023) indicated that factors like nitrogen and phosphorus levels impact tiller numbers. An appropriate amount of P also increases the elongation of *Lolium perenne* (Kavanová et al. 2006).

The SEM analysis performed in this study indicated that biochar's positive effect on switchgrass total weight was mediated through its effect on total P and available N contents in the phosphogypsum substrate (Figure 2d). Li and Cai (2021) found that biochar facilitated plant P assimilation by mediating root morphology and plant phosphorus content. Plants with high tiller numbers and shoot lengths promote more biomass (Zhao et al. 2021). Therefore, the 5% mushroom residue biochar enriched the total weight of switchgrass by increasing tiller number and shoot length in our study.

## 5 | Conclusion

This study highlights the beneficial effects of mushroom residue biochar on the physicochemical properties of phosphogypsum substrate and switchgrass growth. The application of biochar improved substrate properties, including pH, moisture level, organic matter content, and nutrient availability (total and available N, P, and K). The most significant growth improvements were observed at a 5% biochar application rate. Structural equation modeling revealed the mechanisms through which biochar enhances switchgrass growth, emphasizing the pivotal role of pH.

While our findings demonstrate the potential of mushroom residue biochar as an effective soil amendment, it is important to note the limitations of this pot experiment. Future research should explore long-term effects and field conditions, as well as the impact on root morphology and mineral element uptake, to better understand sustainable soil management and cultivation practices.

### Author Contributions

**Yangzhou Xiang:** conceptualization, funding acquisition, investigation, methodology, writing – original draft, writing – review and editing. **Yanting Mao:** conceptualization, funding acquisition, methodology, writing – original draft. **Ying Liu:** conceptualization, funding acquisition, investigation, methodology. **Yang Luo:** investigation, methodology. **Jianming Xue:** methodology, writing – review and editing. **Ji He:** methodology. **Narasinha J. Shurpali**, **Hem Raj Bhattarai**, and **T. K. K. Chamindu Deepagoda:** writing – review and editing. **Bin Yao:** methodology, supervision, writing – original draft, writing – review and editing. **Yuan Li:** funding acquisition, methodology, visualization, writing – original draft, writing – review and editing. **Kadambot H. M. Siddique:** conceptualization, writing – review and editing.

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

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