Supplementary Materials

Section S.1 Germination Rate in Response to Treatments

The germination rate was assessed by counting the number of successfully sprouted sunflower seeds and calculated using the following equation:

$$\text{Germination rate (\%)} = \frac{\text{Number of germinated sprout}}{\text{Number of initial seeds}} \times 100 \quad \text{(S1)}$$

The germination rate of sunflower sprouts was significantly influenced by the type of soil amendment applied (Fig. S1A). The highest germination percentage was observed in the control treatment (97.8%), which did not differ significantly from treatments receiving individual applications of 1% w/w CM, 3% w/w RHB, 0.5% w/w KH, 1% w/w KH, and their respective combinations. These findings suggest that CM and RHB, either alone or in combination with low concentrations of KH, do not adversely affect seed germination. This indicates that, at moderate rates, these amendments are safe for early seedling development and do not create unfavorable soil conditions such as salinity, toxicity, or pH imbalance that could inhibit germination.

The positive results from these treatments can be attributed to their soil-enhancing properties. CM contributes readily available nutrients and improves microbial activity, while RHB enhances soil structure, porosity, and moisture retention without introducing phytotoxic effects. These amendments may help maintain optimal water and nutrient availability during the critical germination phase. These findings align with previous studies, such as those by Minnikova et al. [62], who found no negative impact of biochar on radish seed germination in non-contaminated soil. Similarly, other reports have shown neutral or even beneficial effects of biochar and organic amendments on germination across various plant species [90-91], suggesting that such responses may be plant-specific and context-dependent.

In contrast, higher concentrations of KH significantly reduced sunflower seed germination (Fig. S1A). Application of 2% w/w KH alone drastically decreased germination to 13.3% (−86.4%), and its combination with 3% w/w RHB resulted in the lowest germination rate observed—only 8.9% (−90.9%). Similarly, the 1% w/w CM + 2% w/w KH treatment reduced germination to 66.7% (−31.8%). These reductions are likely due to osmotic stress or salt stress caused by excess KH, which can inhibit water uptake, disrupt seed metabolic processes, and ultimately impair germination [92]. Additionally, high KH concentrations may induce soil aggregate coalescence and compaction, further hindering seedling emergence by reducing pore space and limiting oxygen and moisture availability.

These findings are consistent with those of Piccolo et al. [93], who observed delayed germination in lettuce and tomato due to the application of humic substances—even at low concentrations. However, when KH was applied at moderate levels (0.5–1% w/w), only slight reductions in germination were observed, suggesting that these concentrations may be safer and more appropriate for maintaining a favorable soil environment during germination. Furthermore, the negative effects of KH at higher concentrations appeared to be partially mitigated when combined with CM or RHB. This may be due to the buffering effects of CM's high OM content and RHB's porous structure, which together improve soil aeration, moisture retention, and reduce salt stress. These improvements likely create more favorable conditions for seed germination despite the presence of KH.

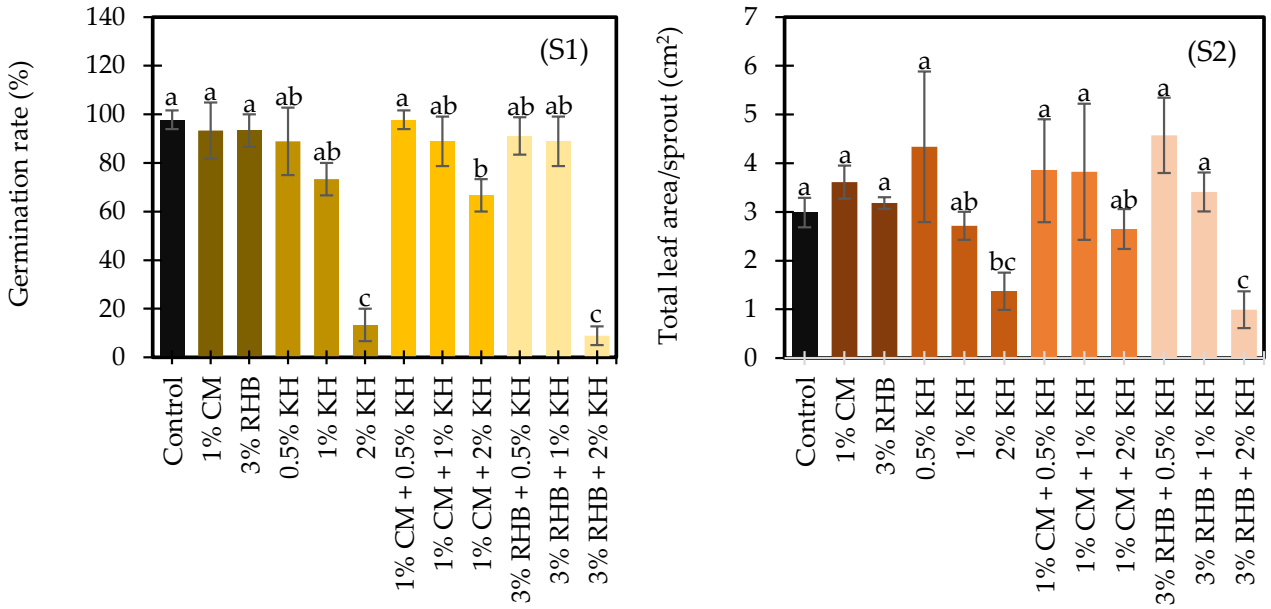


Figure S1. Effects of soil amendments on (A) germination rate and (B) total leaf area per sprout. Bars labeled with different letters (a–e) indicate statistically significant differences among treatments at $p < 0.05$.

Section S.2 Total Leaf Area in Response to Treatments

The width and length of the first and second leaves of each sunflower sprout were measured using a standard ruler. These measurements were used to estimate the average total leaf area per sprout following the approach adapted from Goyne et al. [94], as shown in equation:

$$\text{Average total leaf area} = \frac{\sum((0.73 \times W_1 \times L_1) + (0.73 \times W_2 \times L_2))}{\text{number of sprout}} \quad \text{(S2)}$$

where 0.73 serves as a correction factor, W_1 and L_1 represent the width and length of the first leaf, while W_2 and L_2 correspond to the width and length of the second leaf. All measurements are in centimeters (cm), and the resulting leaf area is expressed in square centimeters (cm^2).

The average total leaf area per sunflower sprout was significantly influenced by the type and combination of soil amendments applied (Fig. S1B). The control treatment recorded an average leaf area of 2.99 cm^2, which served as the baseline. The 2% w/w KH treatment alone reduced the total leaf area by 54.2% (1.37 cm^2) compared to the control. The combination of 3% w/w RHB with 2% w/w KH resulted in the lowest leaf area observed—only 0.99 cm^2—representing a 66.9% reduction. Even the treatment combining 1% w/w CM with 2% w/w KH showed a reduced leaf area of 2.65 cm^2, suggesting that the negative impact of high KH levels may outweigh the potential benefits of organic amendments.

These detrimental effects may be attributed to osmotic stress, salt accumulation, or nutrient imbalances caused by the high KH concentration, which can impair water uptake and disrupt key physiological processes during early seedling growth [95]. Furthermore, elevated KH levels might alter soil structure, leading to the formation of compacted aggregates (Section 3.1.1.) or creating chemically active conditions that restrict root development (Section 3.2.3) and nutrient transport. Such stress conditions reduce photosynthetic efficiency and limit the energy available for leaf expansion [96], ultimately resulting in stunted growth. The particularly low leaf area observed in the 3% w/w RHB + 2% w/w KH treatment underscores this issue, indicating that even the beneficial soil-conditioning

properties of biochar were insufficient to counteract the adverse effects of excessive KH application.

Although most treatments did not significantly increase leaf area compared to the control, several involving moderate KH concentrations or combinations with CM and RHB tended to enhance leaf area. Notably, 0.5% w/w KH increased leaf area by 61.9%, 3% w/w RHB + 0.5% w/w KH by 52.8%, and 1% w/w CM + 0.5% w/w KH and 1% w/w CM + 1% w/w KH by 28.8% and 28.0%, respectively. These results align with previous studies reporting increased leaf area from CM in lettuce [97], RHB in soybean, tomato, and pepper [98-99], and low KH in sugar beet [68]. The observed improvements likely result from enhanced nutrient availability, better soil structure, and stimulated root growth (Section 3.2.1). Additionally, KH may boost chlorophyll biosynthesis (Section 3.3.3) and regulate plant hormones [72], promoting leaf expansion. While not statistically significant, these consistent trends underscore the potential of combining organic and humic amendments to support early sunflower growth.